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66

Compendium of Forest Hydrology and Geomorphology in British Columbia
Volume 2 of 2

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BRITISH COLUMBIA
The Best Place on Earth

Ministry of Forests and Range
Forest Science Program

FORREX
Supporting Sustainable Natural Resource Management Decisions

Compendium of Forest Hydrology and Geomorphology in British Columbia

Volume 2 of 2

Robin G. Pike, Todd E. Redding, R.D. (Dan) Moore, Rita D. Winkler, and Kevin D. Bladon (editors)

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Over the last two decades, hydrologists and geomorphologists have often discussed the need to document the history, scientific discoveries, and field expertise gained in watershed management in British Columbia. Several years ago, a group of watershed scientists from academia, government, and the private sector gathered at the University of British Columbia to discuss the idea of a provincially relevant summary of hydrology, geomorphology, and watershed management. Their main objectives were to bridge the sometimes disparate views in watershed science with an integrated understanding of forest hydrology and geomorphology and to create a "go-to" reference for this information. Through this meeting, the *Compendium of Forest Hydrology and Geomorphology* was born.

As a ***synthesis*** document, the *Compendium* consolidates our current scientific knowledge and operational experience into 19 chapters organized around six themes: the regional context, watershed hydrology, watershed geomorphology, water quality, stream and riparian ecology, and watershed management decision support. These chapters summarize the basic scientific information necessary to manage water resources in forested environments, explaining watershed processes and the effects of disturbances across different regions of the province. Some chapters incorporate case studies highlighting pertinent examples that move discussions from the abstract and theoretical to the applied and practical. Each chapter also presents a comprehensive list of references, many of which are electronically linked for reader convenience. In short, the *Compendium* is about British Columbia and is primarily intended for a British Columbian audience, giving it a uniquely regional focus compared to other hydrology texts.

To ensure that the *Compendium* presented reliable, relevant, and scientifically sound information, chapters underwent extensive peer review employing the standard double-blind protocol common to most scholarly journals. Each chapter was reviewed by three to five peers, several steering committee members, an English editor, and executive reviewers from the B.C. Ministry of Forests and Range and FORREX. With 67 authors and 84 peer reviewers, the *Compendium* embodies the spirit of partnerships—strengthening connections among colleagues, agencies, and disciplines. Although the *Compendium* focusses on British Columbia, its genesis and development involved hydrologists, geomorphologists, and related professionals from across Canada, the United States, and around the world. The "Authors" section (page v) lists all authors and their affiliations, and the "Peer Reviewers" section (page x) provides a record of all peer reviewers.

At over 800 pages, the *Compendium* showcases the rich history of forest hydrology, geomorphology, and aquatic ecology research and practice in British Columbia and sets the foundation for the future by showing us how much more we have yet to learn. We hope it will become a valuable resource for students, water resource professionals, and anyone else interested in water in British Columbia.

Robin G. Pike, Todd E. Redding, R. Dan Moore, Rita D. Winkler, and Kevin D. Bladon
June 2010.

This *Compendium* could not have been produced without the significant efforts of numerous individuals and organizations. We extend our sincerest appreciation and thanks to all who contributed to this project.

FORREX staff provided leadership throughout the project's life. Their commitments to extension and project management ensured that the *Compendium* made that important leap from an idea to a reality. Christine Hollstedt (CEO), Julie Schooling (publications), and Shelley Church (publications) were instrumental in all aspects of the *Compendium*'s development. The Steering Committee also played a crucial role in shaping the *Compendium* by providing the technical direction necessary to keep the project focussed on its objectives. Past steering committee members included Dave Toews, Eugene Hetherington, Doug Golding, and Rob Scherer.

Undoubtedly, the largest contribution was from the *Compendium*'s 67 volunteer authors (see Authors). Words cannot express our deep appreciation of them and their organizations in the development of this project. In addition, 84 provincial, national, and international technical specialists from government, industry, and academia voluntarily peer reviewed all *Compendium* chapters to ensure that high standards were maintained (see "Peer Reviewers").

Several other professionals contributed ancillary information, such as figures or data, that was essential to chapter development, including Anne McCarthy (Environment Canada), Anne Berland (Pacific Climate Impacts Consortium), Joe Alcock (Summit Environmental Consultants Ltd.), David Gluns (B.C. Ministry of Forests and Range), Matt Sakals (B.C. Ministry of Forests and Range), and Dave Toews (B.C. Ministry of Forests and Range). We also thank the following individuals for contributing images to this publication: Dave Gluns (cover), Todd Redding (chapters 1, 12, 15, 16, 17), Dave Polster (chapter 2), Dave Spittlehouse (chapter 3), Robin Pike (chapters 4, 5, 10, 14, 18, 19), Bonnie Pike (chapter 6), Rita Winkler (chapter 7), Marten Geertsema (chapter 8), Peter Jordan (chapter 9), Dave Campbell (chapter 11), and Ian Ricketson (chapter 13).

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We wish to formally thank our colleagues, employers, and funding agencies for their help, support, and patience throughout the *Compendium*'s evolution from concept to completion. We also thank the early hydrologists and geomorphologists who first formulated the idea of a comprehensive document to share their knowledge.

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CHAPTER 12

Water Quality and Forest Management

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INTRODUCTION

Clean water is essential for ecosystems and societies worldwide. In British Columbia, the water that flows from forested watersheds is known for its high quality. Approximately 80% of municipal water in this province is drawn from forested, surface sources; the balance is supplied by groundwater (Bryck 1991; Parfitt 2000). Considering the prevalence of forests as drinking water source areas, management activities that can potentially affect water quality are often a concern to the public.

This chapter provides an overview of factors influencing water quality in British Columbia with a focus on forested watersheds and the management activities conducted in these areas. The chapter provides a review of applicable legislation in British Columbia, describes the B.C. Ministry of Environment's water quality guidelines and objectives, reviews common water quality parameters, and concludes with a review of potential forest management effects on water quality.

WATER QUALITY IN BRITISH COLUMBIA

The term "water quality" is generally used to describe the chemical, physical, and biological characteristics of water, usually with respect to its suitability for a particular use. Streamflow generation mechanisms and flow routing processes are the largest determinants of water quality in forested watersheds (Stednick 2010).

Although rivers and lakes contain low concentrations of dissolved nutrients, nutrient concentrations may spike seasonally because of decomposing salmon carcasses, internal nutrient cycling (e.g., return of phosphorus from lake sediments to the overlying water), nitrogen-fixing plant species, and (or) seasonal movement of accumulated nutrients from soils (Pike and Perrin 2005).

Forests can affect water quality in many ways. Riparian forests provide shade, which moderates water temperatures, and provide a source of organic debris and nutrients, which are used by aquatic organisms. Natural processes in forested areas, such as landslides, channel erosion, blowdown, and wildfire, can affect water quality by creating temporarily increased concentrations of sediment, increased stream temperatures, and (or) increased nutrient concentrations (Harr and Fredriksen 1988). Forests also modify the chemistry of incoming precipitation as a result of vegetation and soil interactions. Nutrient movement within forest ecosystems involves uptake and retention by biota, which retards chemical or nutrient movements to surface waters (Figure

12.1). Thus, natural disturbances and management activities that remove or disturb forest vegetation or alter hydrochemical flow paths may change dissolved and chemical particulate concentrations and fluxes in water bodies.

Across British Columbia, chemical fluxes in forest ecosystems are variable and have been observed to increase, decrease, or remain unaffected by disturbances. Disturbances to these ecosystems include forest harvesting, road construction and use, wildfire, insects, tree diseases, and chemical applications of fire retardants, herbicides, and fertilizers. Other disturbances, such as the clearing of forests for mining, agriculture, or urban development, may also affect water quality (Dissmeyer [editor] 2000; Kaushal et al. 2006; de la Crétaz and Barten 2007), but these activities are not discussed in this chapter.

Important determinants of the chemistry of surface waters flowing from a forested watershed (Feller 2005, 2008) include:

- geological weathering;
- climate: precipitation amount and timing, temperature, and streamflow rates;

FIGURE 12.1 *Forest ecosystems can retard chemical or nutrient movements to surface waters. (Photo: R.G. Pike)*

- precipitation: chemistry of dissolved and particulate materials;
- terrestrial biological processes, including chemical uptake, chemical transformations, and production of soluble chemicals;
- physical-chemical reactions in the soil; and
- physical, chemical, and biological processes within aquatic ecosystems.

Because of the complexity of these factors, the chemical "loading" in streams draining apparently similar watersheds can vary due to small differences in geology, soil, streambed materials, stream shading, or prevailing weather patterns. Chemical fluxes may also vary in time (e.g., annually, seasonally) as a result of changes in weather, precipitation chemistry, and atmospheric deposition. Atmospheric deposition of air pollutants from natural and anthropogenic sources is also a significant source of water quality problems, acidification of streams and lakes, and toxic contamination in many areas (U.S. Environmental Protection Agency 2001). For example, an estimated 80% of the mercury input to Lake Michigan is a result of atmospheric deposition (U.S. Environmental Protection Agency 2001). The monitoring of atmospheric deposition of pollutants to water bodies usually focusses on heavy metals, compounds of sulphur, nitrogen, or mercury, and certain pesticides and herbicides (U.S. Environmental Protection Agency 2001).

Water quality variations over time are also caused by the dilution influence of storm events (Whitfield et al. 1993) or by different seasonal streamflow sources. A flow–dilution relationship is frequently observed in forested watersheds; that is, when streamflow increases, dissolved constituents decrease (e.g., using electrical conductivity as a proxy; Figure 12.2). In areas where base flow is composed largely of groundwater, changes in the proportion of runoff volume to groundwater input will vary over seasons and storm events. After a storm, a river may be composed largely of storm runoff, whereas the pre-storm flow regime may have been predominantly from groundwater. The differences in the chemical composition of these water sources create temporal variability in water quality. At Place Creek near Pemberton, frequent measurements of electrical conductivity were used to identify streamflow sources (Figure 12.3). Other water quality parameters, such as sediment, are often more prominent on the rising limb than on the falling limb of the hydrograph because sediment supply is usually exhausted after

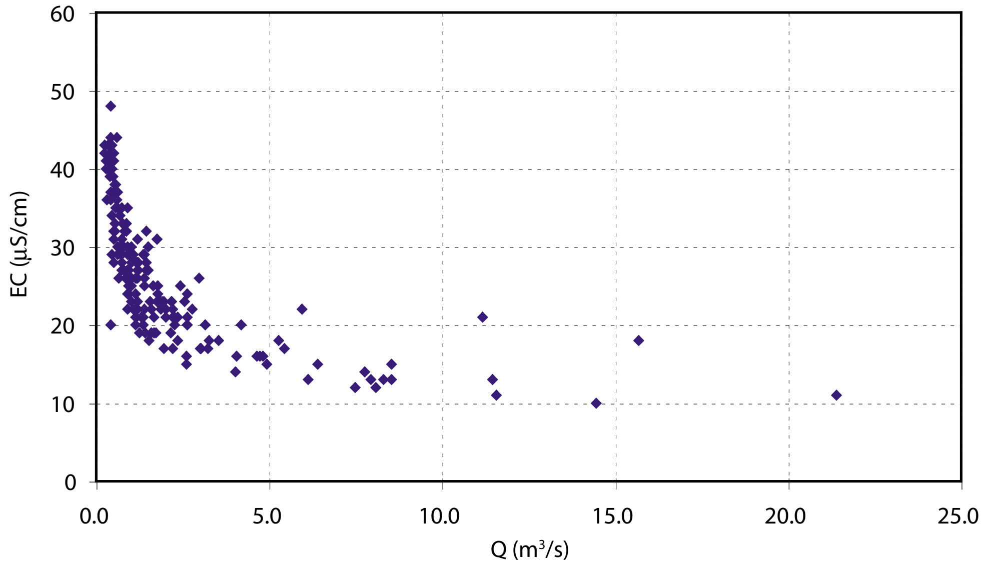

FIGURE 12.2 *Common flow–dilution relationship for a forested watershed in Oregon. Q represents stream discharge; EC represents electrical conductivity, a proxy for dissolved constituents. (Data source: U.S. Geological Survey water quality records; graph: J.D. Stednick, unpublished, 2009).*

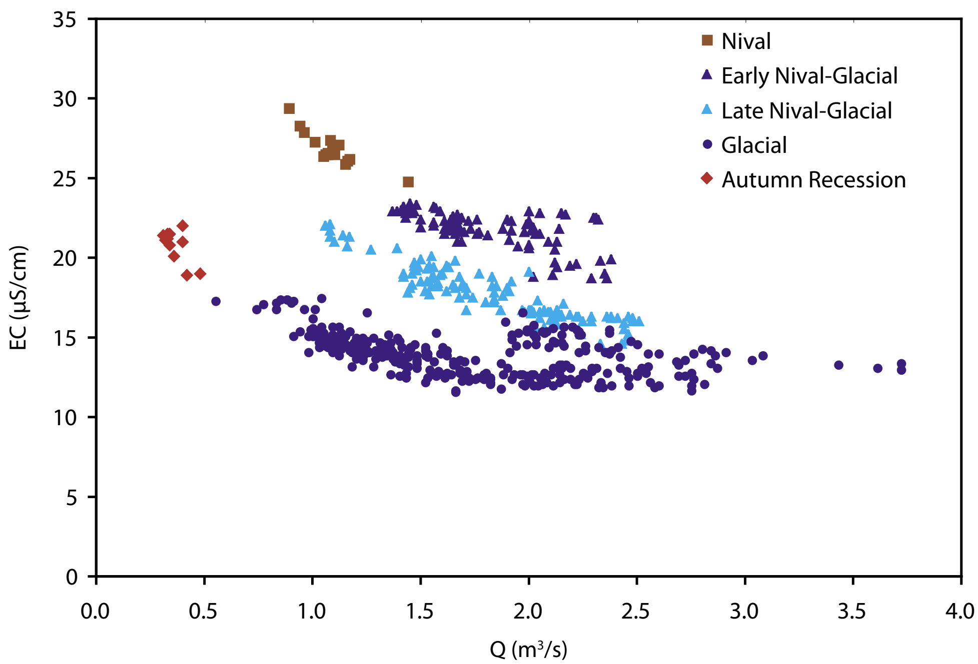

FIGURE 12.3 *Identification of streamflow sources based on the relationship between electrical conductivity (EC) and stream discharge (Q) at Place Creek during the 2000 melt season (Moore et al. 2008a).*

some period of time (Macdonald et al. 2003: see Section 7.3.1, "The Hydrograph").

Although most lakes are similar in chemical composition to the rivers that feed them, reduced water velocity and turbulence in lakes leads to settling of particulates and suspended sediments, lower turbidity, and greater light penetration (Lamb 1985). Most lakes have low water current velocities or multidirectional currents, water residence times of months to years, and periods of thermal or chemical stratification (Meybeck and Helmer 1992). Thermal stratification within lakes can create anaerobic conditions near the lake bottom. Decomposition of organic materials that settle on the lake bottom increases the biological oxygen demand and may deplete dissolved oxygen from the overlying waters. These anaerobic conditions can change the lake oxidation-reduction potential, which creates a reducing environment above the sediments. Such reducing conditions may result in the release of orthophosphate and iron from the lake sediments, which potentially can affect drinking water quality. The internal cycling of major nutrients, such as nitrogen and phosphorus, often leads to greater biological productivity than in rivers and thus differing water quality.

Groundwater frequently has lower mixing rates and generally longer residence times than rivers and lakes; consequently, groundwater is normally more uniform in temperature and exhibits lower variability in chemical composition in time and space than lakes and rivers (Lamb 1985). This can be important for aquatic life. For example, in areas where streams freeze in winter, groundwater inflows can provide temperature refugia for fish and other aquatic life (Power et al. 1999) and (or) can ensure the winter survival of salmon eggs (Leman 1993; Smerdon and Redding 2007).

Water quality naturally varies across British Columbia and can be driven by a watershed's normal hydrologic regime and disturbance agents. Variability in chemical and physical constituents subsequently affects biological water quality. This is important to consider, as this natural variability is the baseline from which the regulation of activities that affect water quality are judged and managed.

GUIDELINES, OBJECTIVES, AND PARAMETERS IN BRITISH COLUMBIA

In British Columbia, the protection of water quality is based on designated water uses at given locations. These uses include:

- drinking water, public water supply, and food processing;
- aquatic life and wildlife;
- agriculture (livestock watering or irrigation);
- recreation and aesthetics; and
- industrial water supplies.

Water quality guidelines and objectives are used to assess water quality so that the most sensitive designated use at a given site can be protected. As such, the standards by which water quality is judged to be acceptable often differ between water uses. For example, water deemed satisfactory for agricultural irrigation may be inappropriate for use as drinking water.

The regulation of activities that affect water quality in forested watersheds in British Columbia (Figure 12.4) is controlled by both federal and provincial governments through various legislative acts and regulations. The following acts and regulations apply to the management of activities on forested Crown land.

- Dam Safety Regulation
- *Dike Maintenance Act*
- *Drinking Water Protection Act*
- *Environmental Assessment Act*
- *Environmental Management Act*
- *Fish Protection Act*
- *Forest and Range Practices Act*
- Groundwater Protection Regulation
- *Ministry of Environment Act*
- Sensitive Streams Designation and Licensing Regulation
- *Utilities Commission Act*
- *Water Act*
- *Water Protection Act*
- Water Regulation
- *Water Utilities Act*

In addition, water quality guidelines and objectives are used in the regulation of water quality in British Columbia.

FIGURE 12.4 *In British Columbia, water quality in forested watersheds is regulated by both federal and provincial governments. (Photo: R.G. Pike)*

Water Quality Guidelines

Water quality guidelines (formerly called "criteria" in British Columbia) provide the benchmark for assessing the province's water quality and setting water quality objectives (see below). Water quality guidelines are numerical values that indicate acceptable levels of physical, chemical, and biological characteristics of water, biota, and sediment for different types of designated water uses. Approved water quality guidelines are applied province-wide to prevent detrimental effects from occurring to a water use, and to support aquatic life. A water quality problem is deemed non-existent if the substance concentration is lower (or higher in some cases, such as dissolved oxygen) than the guideline level; however, this approach does not recognize that the cumulative effect of several substances may cause a water quality problem. Where a guideline is exceeded or falls below a threshold, an assessment of water quality is usually required. British Columbia's water quality guidelines are science-based and subjected to wide review before finalization. Once established, the guidelines are reviewed periodically to incorporate newly available information. Water quality guidelines for the support of aquatic life are the most difficult to develop and are based mainly on the effects of toxins on various life forms. Given the uncertainty involved, conservative safety factors are usually applied in determining the final guideline level. For example, the maximum nitrate guideline is based on the results of toxicity tests with the lowest 96-hour LC_{50},[1] which are multiplied by a safety factor of 0.5, whereas the 30-day average nitrate guideline (again based on the lowest 96-hour LC_{50}) is multiplied by a safety factor of 0.1 (Meays 2009). Provincially approved water quality guidelines take precedence over any other guidelines or standards (e.g., those of the Canadian Council of the Ministers of the Environment or the U.S. Environmental Protection Agency). Approved water quality guideline information for British Columbia can be found on the Ministry of Environment's Environmental Protection Division website at: www.env.gov.bc.ca/wat/wq/wq_guidelines.html.

In situations where guidelines have not yet been fully assessed or endorsed, "working" water quality guidelines are used in British Columbia. These guidelines are obtained primarily from the Canadian Council of the Ministers of the Environment and other North American jurisdictions. The working guidelines provide the best guidance, in the interim, on safe levels of different substances in the environment. Nevertheless, these draft guidelines should always be used with caution because they can be based on historic information or different derivation protocols. Importantly, the appropriate technical document must be used to ensure that approved water quality guidelines are applied correctly.

Water Quality Objectives

Water quality objectives are based on scientific water quality guidelines. These objectives are established on a site-specific basis and take into consideration local water quality, water use, water movement, and waste discharges.

In contrast to the provincially applicable water quality guidelines, water quality objectives are

1 Concentration of toxicant lethal to 50% of test organisms during a defined time period and under defined conditions.

prepared for specific bodies of fresh, estuarine, and coastal marine surface waters. Objectives are prepared only for specific water bodies and water quality characteristics that may be affected by human activity currently or in the future. Water quality objectives are set by the B.C. Ministry of Environment under Section 5(e) of the *Environmental Management Act*. In addition, Section 150 of the *Forest and Range Practices Act* contains provisions for the designation of community watersheds and the establishment of objectives to protect drinking water. For this reason, water quality objectives developed for community watersheds generally focus on potential effects from roads, forest harvesting, and range activities. Currently, 461 community watersheds have been approved in British Columbia. Section 8.2 of the *Forest and Range Practices Act*'s Forest Planning and Practices Regulations contains details on objectives for water in community watersheds.

If water quality objectives for community watersheds are established by the Minister of Forests and Range's order following the *Forest and Range Practices Act*'s Government Actions Regulation process, then those forest agreement holders who are required to prepare a forest stewardship plan must include in this plan a result or strategy consistent with the water quality objective. Objectives are most commonly used to: guide the evaluation of water quality; issue permits, licences, and legal orders; and manage fisheries. The objectives also provide a reference against which the state of water quality in a particular water body can be checked over time.

Water Quality Parameters

Water quality parameters are measures of specific characteristics of water and can be categorized as physical, chemical, and biological parameters (Table 12.1). This section describes some of the most common water quality parameters and serves as an introduction to the example measures. For additional information on water quality parameters and sampling strategies, see the publications listed in Table 12.2.

Water temperature

Water temperature is a physical property of a system defined as the average kinetic energy of atoms in a solution (Stednick 1991) and is a measure of the intensity (not amount) of heat stored in a volume of water. Temperature is measured in degrees Celsius (°C) and is influenced primarily by solar radiation as modified by the seasons, latitude, elevation, vegetation cover, discharge, stream channel characteristics,

TABLE 12.1 *Forest water quality parameters and example measures*

Category	Parameters	Example measures
Physical	Water temperature Sediment	Temperature Total suspended solids Turbidity
Chemical	Ions, dissolved constituents, and nutrients	pH Electrical conductivity Total dissolved solids Dissolved oxygen Ions (e.g., sodium, potassium, calcium, magnesium, iron) Nitrogen (nitrate, ammonium) Phosphorus (various forms)
	Toxic parameters	Pesticides (insecticides, herbicides, and fungicides) Metals (e.g., lead, mercury, cadmium, aluminum, copper, selenium, zinc)
Biological	Biological parameters	Chlorophyll *a* Fecal coliform Benthic invertebrate communities

TABLE 12.2 *Water quality sampling literature*

Title	Author (year)
Ambient Freshwater and Effluent Sampling Manual	Resources Information Standards Committee (1998)
British Columbia Field Sampling Manual	Clark (editor, 2003)
Continuous Water Quality Sampling Programs: Operating Procedures	Resources Information Standards Committee (RISC) 2006a
Continuous Water Quality Sampling Programs: Appendices	Resources Information Standards Committee (RISC) 2006b
Freshwater Biological Sampling Manual	Cavanagh et al. 1997[a]
Guidelines for Designing and Implementing a Water Quality Monitoring Program in British Columbia	Cavanagh et al. 1998a
Guidelines for Interpreting Water Quality Data	Cavanagh et al. 1998b
Guidelines for Monitoring Fine Sediment Deposition in Streams, Version 1.3	Rex and Carmichael 2002
Lake and Stream Bottom Sediment Sampling Manual	Resources Information Standards Committee 1997

a Resources Information Standards Committee approved protocol.

cloud cover, and time of day. In British Columbia, measured surface water temperatures (Figure 12.5) can naturally range from less than 0°C under ice to more than 40°C in hot springs. For additional information on water temperature variability and measurement, see Chapter 17 (“Watershed Measurement Methods and Data Limitations”).

Changes to water temperature regimes (water temperature over time) beyond optimal ranges can have significant effects on aquatic life, such as fish (e.g., metabolic rates, eggs, behaviour, and mortality). Increasing water temperature may lead to more rapid decomposition of organic material, which in turn could result in decreased oxygen levels. Increased temperatures also elevate metabolic oxygen demand, which in conjunction with reduced oxygen solubility, may affect aquatic species. In most mountain streams, however, high aeration rates preclude significant changes in dissolved oxygen content (Brown and Beschta 1985; Stednick 1991). Temperature also affects the solubility of many constituents such as metals that may influence water quality. Information on preferred temperatures for spawning and incubating salmon and lower or upper lethal and preferred temperatures for select salmon species can be found in Bjornn and Reiser (1991).

Water temperature guidelines vary depending on water use (e.g., consumptive use vs. aquatic life). A summary of guidelines for water temperature follows; for complete details on each of these guidelines, see Singleton (2001):

- Drinking water: maximum of 15°C for aesthetics.
- Aquatic life (streams with known fish distribution): ±1°C beyond optimum temperature range for the most sensitive species present.
- Aquatic life (streams with unknown fish distributions): mean weekly maximum temperature of 18°C or less.

FIGURE 12.5 *Measuring stream temperature in a British Columbia coastal stream. (Photo: T. Redding)*

Sediment: Total suspended solids and turbidity
Clay, silt, and very fine sand particles less than 0.1 mm in diameter can be transported as suspended sediment (MacDonald et al. 1991) in water at most velocities. Fine sediment in forested watersheds is generally measured as total suspended solids (TSS) or turbidity (Stednick 1991).

Total suspended solids Total suspended solids (also known as non-filterable residue) refer to the portion of sediments suspended in a water column. Suspended sediment is measured by drying or filtering a water sample (usually a depth-integrated sample) and weighing the residual portion, which is expressed as a concentration in milligrams per litre (mg/L) or parts per million (ppm).

Fine sediment has many important implications for water quality (Figure 12.6). In addition to restricting light penetration in water, suspended solids can result in damage to fish gills and impair spawning habitat by smothering fish eggs. Suspended solids can also impair water treatment processes (Cavanagh et al. 1998b).

Guidelines for TSS are based on increases over background levels. These guidelines can be either pre-operational, whereby monitoring must be done to establish appropriate background levels, or post-operational, whereby a site upstream of the anthropogenic influences contributing to increased turbidity is used to define background (see Caux et al. 1997). In British Columbia, TSS guidelines have been developed for aquatic life and for other uses. A summary of TSS guidelines to protect aquatic life follows; for complete details on each of these guidelines, see: www.env.gov.bc.ca/wat/wq/BCguidelines/turbidity/turbidity.html.

- Induced suspended sediment concentrations should not exceed background levels by more than 25 mg/L at any one time for a duration of 24 hours, or exceed 5 mg/L from background at any one time for a duration of 30 days, in all waters during clear flows.
- Induced suspended sediment concentrations should not exceed background levels by more than 25 mg/L at any time when background is 25–100 mg/L during high flows or in turbid water.
- When background exceeds 100 mg/L, suspended sediments should not be increased by more than 10% of the measured background level at any one time.

Details of methods commonly used to sample suspended sediments are presented in Chapter 17, "Watershed Measurement Methods and Data Limitations" (see subsection on "Suspended Sediment").

FIGURE 12.6 *Suspended sediment in streams can have many important implications for water quality. (Photo: P. Teti)*

Turbidity Turbidity is used as a proxy to describe sediment content of water samples (Figure 12.7). Turbidity refers to the amount of light scattered by a fluid (Stednick 1991) and is measured in nephelometric turbidity units (NTU). Increasing turbidity is usually associated with increasing suspended sediment concentrations. Turbidity cannot be used as a direct measure of suspended sediment as values are influenced by solution colour, particle size, particle shape, solute concentration, and dissolved air (Anderson and Potts 1987); however, relationships between turbidity and suspended sediment may be developed on a site-specific basis (Stednick 1991). Details of methods commonly used to measure turbidity are presented in Chapter 17, "Watershed Measurement Methods and Data Limitations" (see subsection on "Turbidity as a Proxy for Suspended Sediment").

Excessive sedimentation rates can adversely affect aquatic life as fine sediment can fill gravel interstices, thereby reducing oxygen availability for developing fish eggs and embryos (Fredriksen 1973). Prolonged turbid waters also block light, which reduces primary productivity. Excessive turbidity negatively affects the aesthetics associated with recreational water use. Turbid waters also require higher levels of treatment if used for drinking water because of the increased total available surface area of solids in suspension upon which bacteria can grow. Turbidity also interferes with the disinfection of drinking water and is aesthetically unpleasing (Cavanagh et al. 1998b).

As with TSS, turbidity guidelines are based on increases over background levels. A summary of turbidity guidelines follows; for complete details, see Caux et al. (1997) or www.env.gov.bc.ca/wat/wq/BCguidelines/turbidity/turbidity.html.

FIGURE 12.7 *Measuring the turbidity of a water sample. (Photo: P. Teti)*

- For raw drinking water with treatment for particulates: turbidity should not increase from background by more than 5 NTU when background is less than or equal to 50 NTU, or should not change from background by more than 10% when background is greater than 50 NTU.
- For raw drinking water without treatment for the removal of particulates: turbidity should not increase from background by more than 1 NTU when background is less than or equal to 5 NTU, or should not change from background by more than 5 NTU at any time when background is greater than 5 NTU.

Turbidity guidelines for other water uses are also dependent on background levels and have specific requirements for determining attainment (Caux et al. 1997).

pH, electrical conductivity, total dissolved solids, dissolved oxygen, nitrogen, and phosphorus

pH The pH of a substance is a measure of hydrogen ion (H^+) activity. The "H" in "pH" represents the moles per litre of H^+ and "p" is the negative log; thus, a H^+ activity of $10^{-5.6}$ is expressed as a pH of 5.6. A 14-point scale is used to quantify pH: less than 7 is acidic, 7 is neutral, and greater than 7 (up to 14) is basic. For solutions in which the concentration of hydrogen ions (H^+) is higher than hydroxide ions (OH^-), the solution will be acidic (i.e., pH < 7). For solutions in which hydroxide ions have a higher activity than H+, the solution will be basic (pH > 7).

Various methods are used to measure pH, the most common of which is colour indicators (e.g., litmus strips) or specialized probes that generate voltage proportional to the pH of a solution. A comprehensive review of pH determination and measurement is available in McKean and Huggins (1989).

In British Columbia, the range of pH in surface water is variable and is largely a product of the amount of precipitation and the rate of geologic weathering in soils and bedrock (McKean and Nagpal 1991). Regarding water quality, pH is important as it determines the solubility of heavy metals. McKean and Nagpal (1991) outlined the following ways in which pH can affect aquatic organisms.

- alteration of chemical species (metals, etc.) to toxic forms
- destruction of gill tissue
- creation of acidosis or alkalosis

- loss of electrolytes
- inhibition of ammonia excretion mechanism

Guidelines for pH vary depending on water use (e.g., drinking vs. aquatic life). Additionally, some other guidelines are pH-dependent and are adapted for conditions at the site (e.g., ammonia). Further details on ambient water quality criteria for pH are found in McKean and Nagpal (1991) and in Table 12.3 below.

Electrical conductivity Electrical conductivity (EC) is a measure of the ease with which electrical current passes through water, and is expressed in microSiemens per centimetre (μS/cm). The EC of water varies with ion composition, ion concentration, and temperature (Moore et al. 2008a). Because of the temperature dependence, the measurement of EC is corrected to a standard temperature (e.g., 25°C). The term "specific conductance" (SC) refers to electrical conductivity measured at a specified reference temperature, usually 25°C (Moore et al. 2008a), and is often considered synonymous with electrical conductivity (Mills et al. 1993).

Electrical conductivity is used as an indicator of water chemistry and hydrologic processes (Figures 12.2, 12.3, 12.8), and is also used to identify groundwater discharge zones. The introduction of tracers that temporarily alter water EC (e.g., sodium chloride) are used to measure stream discharge (Moore 2004a; 2004b; Hudson and Fraser 2005; Moore et al. 2008a).

Additional information on the use of electrical conductivity as an indicator of water chemistry and hydrologic process can be found in Moore et al. (2008a).

Total dissolved solids Total dissolved solids (TDS) is a measure of inorganic salts dissolved in water. The principal constituents are usually calcium, magnesium, sodium, potassium, carbonate, bicarbonate, chloride, sulphate, phosphate, and nitrate (Health Canada 1978). These dissolved solids come from both natural and human sources (road salt, fertilizer, etc.), and as such, concentrations vary across British Columbia. In general, concentrations of TDS in drinking water are well below 500 mg/L but may be higher in some areas (Health Canada 1978). It is measured by collecting electrical conductivity data and converting it to TDS values using a multiplication factor (0.55–0.8) (Health Canada 1978); it is also measured gravimetrically (Health Canada 1978).

Dissolved oxygen Dissolved oxygen (DO) is a measure of the amount of oxygen dissolved in water through diffusion from the air, aeration or turbulence in a stream, or photosynthesis occurring in aquatic ecosystems. Most aquatic organisms require DO. In British Columbia, DO levels in surface waters are usually high. Saturation levels are the maximum level of DO that can be contained in the water, based on water temperature and partial pressure of atmospheric oxygen, and are often greater than 10 mg/L (B.C. Ministry of Environment 1997).

Dissolved oxygen is most often measured in situ through the use of specialized probes and data loggers. Measuring DO in the laboratory via grab samples may cause errors in accuracy compared to *in situ* conditions. For more information on DO and its measurement, see B.C. Ministry of Environment (1997). Guidelines for DO in British Columbia are also available at: www.env.gov.bc.ca/wat/wq/BCguidelines/do/index.html.

Nitrogen In relation to the potential effects of forest management activities on chemical water quality, changes to nitrogen (N) and phosphorus (P) inputs are considered important (Brown and Binkley 1994).

TABLE 12.3 *Summary of surface water pH guidelines in British Columbia*

Water use	Guidelines for pH units	Comments
Drinking water supply	pH 6.5–8.5	Designed to minimize solubilization of heavy metals and salts from water distribution pipes and the precipitation of carbonate salts in the distribution system, and to maximize the effectiveness of chlorination; however, natural-source water outside the guidelines may be safe to drink from a public health perspective.
Recreational waters	pH 5.0–9.0	No irritation to eyes. Note that lakes with naturally low or high pH are not in contravention of the guideline.

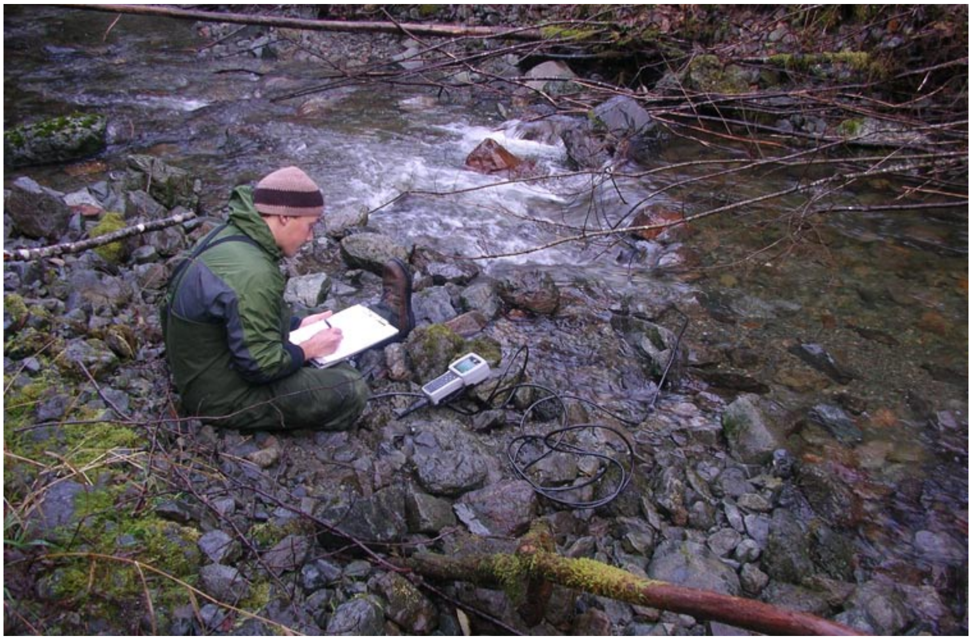

FIGURE 12.8 *Measuring electrical conductivity in a British Columbia coastal stream. (Photo: D. Spittlehouse)*

Nitrogen and phosphorus typically limit terrestrial and aquatic productivity, respectively, and increased concentrations can lead to eutrophic conditions in aquatic environments (Binkley and Brown 1993). Excessively high levels of nitrate can be toxic to fish (Stednick [editor] 2008). Nitrate-N concentrations greater than 10 mg/L can also adversely affect human health and can cause methaemoglobinaemia or "blue baby" syndrome (Binkley et al. 1999a).

Nitrate and ammonium are the primary constituents of interest when considering nitrogen. Nitrate (NO_3^-) ions are formed through the oxidation of nitrogen by micro-organisms in plants, soil, or water, and to a lesser extent, by electrical discharges such as lightning (Beatson 1978). In North America, background concentrations of nitrate-N in streams are low and average 0.31 mg/L with a median value of 0.15 mg/L (Binkley 2001). Concentrations are typically lower than this in British Columbia's coastal streams, and sometimes are as low as 0.010 mg/L (Perrin et al. 1987). Nitrite (NO_2^-) is another form of nitrogen that tends to oxidize rapidly to nitrate in the environment. Nitrite is rare in forested watersheds. Detectable concentrations in surface waters often suggest an input of organic waste such as sewage. Water quality guidelines for nitrate and nitrite are summarized in Table 12.4.

Ammonia (NH_3) is a colourless gas that has a strong pungent odour. Ammonia is produced naturally by the biological degradation of nitrogenous matter (e.g., amino acids) and is an essential link in the nitrogen cycle (Health Canada 1987). Ammonia concentrations as low as 0.03 mg N/L can be potentially toxic to aquatic organisms in the short term; concentrations greater than 0.002 mg N/L may be toxic over the long term (Binkley et al. 1999a, 1999b).

TABLE 12.4 *Summary of British Columbia water quality guidelines for nitrate and nitrite (Meays 2009)*

Water use	Nitrate (mg/L as nitrogen)	Nitrite (mg/L as nitrogen)
Drinking water	10 mg/L (maximum)	1 mg/L (maximum)
Freshwater aquatic life (maximum)	31.3 mg/L (maximum)[a]	0.06 mg/L (maximum)
Freshwater aquatic life (average)	3.0 mg/L (30-d average)[a]	0.02 mg/L (average) when chloride is ≤ 2 mg/L

a Source: http://a100.gov.bc.ca/pub/eirs/viewDocumentDetail.do?fromStatic=true&repository=EPD&documentId=9930).

The conversion of ammonium (NH_4^+) to ammonia (NH_3) is pH-dependent. Both ammonia and ammonium can exist in water, but ammonia is stable only when pH is greater than 9. Concentration of ammonia decreases tenfold with each decrease in pH unit; thus, for acidic forest soils (pH 4–6.5), ammonia concentrations are typically below detection limits (Binkley et al. 1999a). Ammonium concentrations are also typically below detection limits in surface waters, since ammonium is rapidly utilized in plant uptake or fixed on soil cation exchange sites.

Phosphorus Phosphorus (P) is often the nutrient that limits biological production in aquatic ecosystems. Overloading a system with phosphorus can lead to excess production of unwanted algae, as well as other water quality problems, including reduced oxygen content, which can kill fish and may lead to drinking water impairment (taste, odour, and treatment difficulties) (Wetzel 2001). The magnitude of the effect depends on the characteristics of the receiving water body (e.g., discharge, background phosphorus concentration, and water residence time) (Pike and Perrin 2005).

Phosphorus is naturally derived mainly from the weathering of minerals. The cycling of phosphorus between plants, animals, soils, and water involves both dissolved and particulate forms of the element (Scatena 2000). In freshwater, phosphorus occurs in three forms: (1) inorganic phosphorus, (2) undissolved or particulate organic phosphorus, and (3) dissolved organic phosphorus (Environment Canada 2005). Phosphorus dissolved in water usually occurs in the form of phosphates (PO_4^{3-}). In North America, more particulate than dissolved phosphorus occurs in stream water (Feller 2008). Unlike nitrogen, phosphorus does not have a gaseous component (Scatena 2000). Sources of phosphorus include agricultural and urban runoff, soil erosion, and sewage.

Phosphorus is not considered hazardous to human health (Scatena 2000). In British Columbia, guidelines for phosphorus vary between lakes and streams (Nordin 1985). Currently, approved water quality guidelines for phosphorus are based on *Water Quality Criteria for Nutrients and Algae* www.env.gov.bc.ca/wat/wq/BCguidelines/nutrients/nutrientstech.pdf). A summary of the phosphorus guidelines for lakes follows.

- Drinking water sources: < 10 μg/L total P
- Recreation: < 10 μg/L total P
- Aquatic life: 5–15 μg/L total P (for lakes with salmonids as the predominant fish species).

For streams, chlorophyll *a* is used as the water quality measure because several conditions (i.e., water velocity, substrate, light, temperature, and grazing pressure) must be met before phosphorus becomes a factor causing nuisance levels of algal growth (Nordin 1985). As algal biomass is the focus of concern it was chosen as the measure (Nordin 1985). A summary of the guidelines for chlorophyll *a* follows.

- Drinking water sources: no recommendation
- Recreation: < 50 mg/m^2 chlorophyll *a*
- Aquatic life: < 100 mg/m^2 chlorophyll *a*

Other biological and toxic parameters
Water quality analysis in forested ecosystems can also focus on several other parameters. Biological parameters of interest often include total coliforms, *Cryptosporidium*, and *Giardia*. Further discussion of these constituents and the factors influencing their generation and transport to water bodies can be found in Dissmeyer (editor, 2000) and Scatena (2000).

Toxins can be defined as any chemicals that cause adverse effects (Brown and Binkley 1994). Acute toxicity occurs in the short term and is the rapid response of organisms to a chemical dose (Norris and Moore 1976). Chronic toxicity occurs over the long term and is the delayed response of organisms to the exposure of a chemical (Norris and Moore 1976). Examples of toxins that may be monitored in water include heavy metals, such as lead or cadmium, or pesticides.

Biological parameters and toxins are generally monitored in association with land use (e.g., agriculture, range) or point and non-point source discharges (e.g., mineral extraction, urban stormwater/sewer, pulp mill effluent, wildlife/cattle). Approved water quality guidelines for biological and toxic parameters in British Columbia are available from: www.env.gov.bc.ca/wat/wq/BCguidelines/approv_wq_guide/approved.html. Working guidelines are available at: www.env.gov.bc.ca/wat/wq/BCguidelines/working.html.

In the last 20 years, numerous reviews of forest management effects on water quality have been published, including those of Krause (1982), Hetherington (1987), MacDonald et al. (1991), Binkley and Brown (1993), Brown and Binkley (1994), MacGregor (1994), Martin (1995), Miller et al. (1997), Teti (1998), Carignan and Steedman (2000), Dissmeyer (editor, 2000), and Sedell et al. (2000). A summary of water quality components that can be affected by forest management activities is presented in Table 12.5.

Forest Management Effects on Sediment and Water Temperatures

Increased sediment inputs and stream temperatures are two common concerns associated with the effects of forest management on water quality. Because several different natural disturbances and forest practices can affect sediment and stream temperature in British Columbia, the coverage of these topics has occurred extensively throughout many other chapters in this Compendium. Specifically, the reader is referred to the following information.

- Groundwater influence on stream temperatures (Chapter 6)
- Riparian management effects on stream temperature (Chapter 15)
- Stream temperature measurement (Chapter 17)
- Climate change, stream temperature, and water quality (Chapter 19)
- Modelling future stream temperatures (Chapter 19)
- Glaciation, geology, and effects on sediment regimes (Chapter 2)
- Landslides, erosion, and sedimentation processes (Chapter 8)
- Forest management and sediment production (Chapter 9)
- Sediment influence on stream channel morphology (Chapter 10)
- Sediment production in karst environments (Chapter 11)
- Sediment and stream/riparian ecology (Chapter 13)
- Sediment and salmon (Chapter 14)
- Riparian management, sediment production, and stream habitat (Chapter 15)
- Practices to avoid harvesting-related landslides and sediment production (Chapter 9)
- Practices to avoid landslides and sediment production from forest roads (Chapter 9)

TABLE 12.5 *Components of water quality potentially affected by forest management activities*

Activity	Variants	Affected water quality components
Timber harvesting	Clearcutting Variable retention	Temperature, sediment, nutrients, dissolved solids, dissolved oxygen
Timber extraction	Tractor (crawler or wheeled) Rubber-tire skidder Cable yarding (ground lead, high lead, skyline) Helicopter	Sediment, dissolved solids
Roads and stream crossings	Road construction, use, maintenance, and deactivation Bridge and culvert installation	Temperature, sediment, toxins, dissolved solids, dissolved oxygen
Site preparation	Mechanical preparation, scarification, slash disposal	Sediment, nutrients, dissolved solids, dissolved oxygen
Prescribed burning	Broadcast, pile and burn	Nutrients, sediment, dissolved solids, dissolved oxygen
Applied chemicals	Fertilizers Pesticides and herbicides Fire suppressants and retardants	Nutrients, toxins Toxins, temperature Nutrients, toxins

- Climate change effects on landslides, glaciers, and sediment (Chapter 19)
- Measuring suspended sediment and turbidity (Chapter 17)
- Sediment source mapping (Chapter 17)
- Riparian assessment and fine sediment (Chapter 15)
- Watershed assessment and sediment (Chapter 16)
- Sediment in forested watersheds and rehabilitation measures (Chapter 18)

Therefore, this chapter will not duplicate these sources of information. Rather, the following material briefly highlights these parameters from a water quality perspective. The reader should consult the sources listed above for more detailed information.

Stream temperature

Stream temperature is influenced by various energy sources including short- and long-wave radiation, sensible and latent heat from the atmosphere, conduction from the streambed, and advective inputs from groundwater, hyporheic, and tributary inflows (Moore et al. 2005). All of these energy sources vary in response to daily and seasonal cycles of climatic variables as well as synoptic-scale weather systems. As a result, stream temperatures also vary on daily, synoptic, and seasonal time scales. The influence of groundwater on stream temperature is discussed further in Chapter 6, "Hydrologic Processes and Watershed Response."

Stream temperature sensitivity to hydroclimatic conditions varies with both riparian vegetation cover and channel morphology. The riparian forest canopy provides shade, emits long-wave radiation, and reduces wind speed, thus exerting an important control on the radiative and turbulent exchanges at the stream surface. The effects of the forest canopy vary with stream width, as a wider stream has a greater sky view factor and thus reduced shading and longwave radiation and higher wind speeds over the stream. The sensitivity of stream temperature to energy inputs is inversely related to stream depth. As a result of these factors, wide, shallow streams in undisturbed riparian zones are generally more sensitive to heating than deep, narrow streams with a similar discharge.

Stream temperature exhibits systematic variability within and among catchments. Within a catchment, stream temperature is generally coldest in the headwaters and increases downstream for both glacier-fed and groundwater-fed streams. Particularly on the interior plateaus, many catchments contain lakes and wetlands that become much warmer than groundwater during periods of calm, sunny weather. This warming produces elevated stream temperatures at the outlets of lakes and wetlands, with cooling in downstream reaches caused by inflow of colder groundwater (Mellina et al. 2002). Among catchments, stream temperature tends to increase with fractional lake coverage and to decrease with mean catchment elevation and fractional glacier coverage, as the increased inputs of cool water during periods of warm weather serve to moderate diurnal warming (Moore 2006). It is expected that a continued reduction in meltwater contributions associated with glacier retreat will lead to altered aquatic habitat characteristics, including increased stream temperatures and altered stream water chemistry (see Chapter 19, "Climate Change Effects on Watershed Processes in British Columbia"). A complete description of how stream temperature may be affected by climate and climate change is provided in Chapter 19.

Forest harvesting has the potential to influence stream temperature in several ways. Harvesting in riparian areas can affect stream temperature directly through the removal of shading vegetation and alteration of riparian microclimate. Riparian forest harvesting can also cause stream widening caused by the loss of bank strength as tree roots decay, resulting in greater temperature response to heat inputs. Forest harvesting outside the riparian zone can also lead to channel destabilization and widening as a result of increased inputs of coarse sediment and discharge, particularly where debris flows occur (Chapter 15, "Riparian Management and Effects on Function"). Forest harvesting has led to increases in stream temperatures in all seasons, with the greatest increases occurring in the summertime (see Table 15.12 for details).

Stream temperature is an important water quality parameter as it has a strong influence on metabolic rates, biological activity, and decomposition that can affect the chemical and biological composition of waters. Altering stream temperatures thus has the potential to have a strong influence on local biological communities. Certain fish species in British Columbia, such as the bull trout (*Salvelinus confluentus*), have been shown to be sensitive to temperature changes. Overall, responses to increased water temperatures, and how these changes will affect the various life stages (from egg to spawning adult) are generally defined by fish species. For example, at Carnation Creek, minor changes in stream temperatures in the fall and winter caused by forest harvesting profoundly affected salmonid populations, accelerating egg and alevin development rates, emergence timing, seasonal growth, and the timing of seaward migration (Tschaplinski et al. 2004). Further details of the influence of riparian management on stream temperature can be found in Chapter 15, "Riparian Management and Effects on Function."

Sediment

The production of sediment and movement to streams and lakes in British Columbia is caused by both natural and human-caused factors (Figure 12.9). Primary sources of sediment include surface erosion, mass movements (e.g., landslides), and streambank erosion (Hetherington 1987). Importantly, each sediment source contributes different calibres (sizes) of sediment at different time intervals. Mass movements contribute large and fine sediment fractions episodically (see Chapter 8, "Hillslope Processes," Chapter 9, "Forest Management Effects on Hillslope Processes," and Chapter 10, "Channel Geomorphology: Fluvial Forms, Processes, and Forest Management Effects"). In contrast, surface erosion generally contributes finer sediments continually, which can have an important effect on drinking water quality, aquatic life, and habitat conditions. The size of the sediment (i.e., coarse fractions) is one of the most significant of the potential factors influencing channel morphology (Figure 12.9; see also Chapter 10).

Historically, forest management increased the production and movement of sediment to waterways directly through practices such as: the logging of floodplains, fans, and riparian forests; cross-stream yarding; harvesting unstable or marginally stable terrain; road construction causing landslides and surface erosion; inadequate stream crossings; and indirectly through channel and bank destabilization (for a more complete history, see Chapter 18, "Stream, Riparian, and Watershed Restoration"). These historic practices have largely been discontinued or have been modified to reduce the potential for sediment transport. In more recent times, timber harvesting has been shown to have minimal direct effects on sedimentation levels (Egan 1999; and see Chapter 9, "Forest Management Effects on Hillslope Processes"). Stream crossings by roads or skid trails are the most frequent sources of sediment input because these crossings act as focal points for the introduction of sediment into streams (Taylor et al. 1999) from road surfaces and ditch-lines. Natural sediment production in any given watershed is generally related to precipitation and snowmelt events, and the degree of connectivity of sediment source to waterway. So while certain forestry practices in

FIGURE 12.9 *The production of sediment and movement to streams and lakes in British Columbia is caused by both natural and human-caused factors. (Photo: R.G. Pike)*

some areas may increase the potential for sediment production, precipitation will still be a key factor (Chapter 16, "Detecting and Predicting Changes in Watersheds").

Sediment is an important water quality parameter because it can directly influence aquatic organisms as well as water treatment effectiveness. For example, sediment particle size distribution of incubation gravels and the percentage of fine sediments (e.g., < 0.85 mm diameter) (Chapman 1988; Young et al. 1991) in streams can have a strong influence on egg survival to emergence for salmon and trout (Chapter 14, "Salmonids and the Hydrologic and Geomorphic Features of Their Spawning Streams in British Columbia"). Fine sediment can reduce intergravel water flows, decrease the supply of dissolved oxygen to the eggs and alevins, and decrease the transport of ammonia and other metabolites away from the egg pockets (Chapter 14).

Forest Management Effects on Nutrients

Nutrient uptake

Nutrient cycling in forested environments is often complex and dependent on ecosystems, vegetation species, and structure. In general, forest harvesting initially reduces nutrient uptake by terrestrial vegetation, which may lead to increased nutrient concentrations and loads in aquatic ecosystems for periods of 1–7 years for nitrogen and up to 10 years for base cations. Conceptually, nutrient loading initially increases after forest harvesting, then declines when local plant uptake is at a maximum (e.g., at canopy closure); however, forest harvesting effects differ depending on forest species composition and structure (including understorey vegetation). The following four subsections are based on literature reviews conducted by Feller (2005, 2008). The reader is directed to these reviews for additional detail and supporting references.

Nutrient transformations

Forest harvesting can affect microbiologically mediated soil processes. For example, the creation of forest openings by harvesting or canopy gaps by blowdown, or the falling of old-growth trees, can increase nitrification in the soil (Feller 2005, 2008). This may increase nitrate flow through the soil, which may reach surface water bodies. This flow may be enhanced if nitrogen fixation also increases after forest harvesting. For example, nitrogen fixation may increase if the cover of nitrogen-fixing plant species, such as *Alnus* spp. (alder), increases after forest harvesting (Feller 2005, 2008), particularly when alder is part of the riparian vegetation (Stednick [editor] 2008). Nitrogen fixation increases existing nitrogen pools and may increase nitrate mobility. Conversely, nitrate flow can decrease in forests because of denitrification, especially in riparian forests where anaerobic conditions may result from increased soil moisture and increased dissolved organic carbon (DOC) in soil solution (caused by enhanced decomposition of organic material) (Feller 2005, 2008). Recognition of this process is commonly used in designing riparian or streamside management zones to improve water quality from upslope sources (Stednick 2010).

Production of soluble constituents

In general, forest harvesting deposits variable amounts of organic material and litter on the soil surface. Harvesting in the riparian zone may cause an initial decrease in forest litter production and result in less organic matter input into streams immediately following harvesting. Organic material and litter produces easily soluble constituents, which are leached into the soil or water as the material decomposes. This may not always contribute to enhanced soil nitrogen availability following harvesting. Forest harvesting has a variable effect on litter decomposition rates because of differences in the type of material being decomposed, the climate, the effects of harvesting on soil organisms, and the degree of mixing of organic matter with soil materials (Feller 2005, 2008).

Process effects within aquatic ecosystems

Forest harvesting can influence many processes within aquatic ecosystems, but the extent of this influence depends on the amount of organic debris, fine sediment, and solar radiation reaching the aquatic ecosystem. Increases in ion exchange, chemical oxidation-reduction reactions, and microbial transformations all increase with the surface area of the streambed substrate. Although many studies have investigated chemical cycling processes within undisturbed forested streams, the direct effects of forest harvesting on these processes has not been widely studied (Feller 2005).

Primary production in a stream ecosystem increases with solar radiation and with temperature. When these parameters increase because of forest harvesting, primary production may also increase.

Other factors

Chemical loading is further influenced by the characteristics of the harvesting itself, soil properties, and the rate of re-vegetation following harvesting (Figure 12.10). Specifically, these influencing factors include:

- proportion of the watershed harvested;
- presence of riparian reserves between freshwater and disturbed areas;
- nature of the site treatment following forest harvesting;
- rate of re-vegetation following harvesting;
- nutrient content of the soil (soil fertility) before harvesting;
- buffering capacity of the soil;
- abundance of water storage areas in a watershed; and
- timing of forest harvest.

In general, the greater the proportion of the watershed harvested, the greater the effects on constituent movement through the watershed (Feller 2005; Gundersen et al. 2006; Titus et al. 2006).

Undisturbed vegetated strips adjacent to a water body can effectively remove sediments and nutrients flowing from a harvested area upslope of the water body (Figure 12.11). The filtering efficiency of these vegetated strips generally increases as the width of the strip increases. It has been suggested that 100% removal of excess nutrients occurs when widths are greater than 100 m (Feller 2008); however, the effectiveness of buffer strips varies by watershed and depends on other factors, such as soil properties, slope angle, subsurface hydrology, presence or absence of small ephemeral channels running through the buffer strips to the water body, and the type of vegetation present (Vidon and Hill 2006; de la Crétaz and Barten 2007; Mayer et al. 2007; Feller 2008).

Site preparation treatments, such as mechanical scarification, slashburning, or herbicide application, can potentially increase the effects of timber harvesting on stream water chemistry. Clearcutting plus slashburning may cause more change in stream water chemistry than clearcutting alone. Herbicide applications to control competing vegetation following clearcutting can cause the greatest observable changes in stream water chemistry. For example, Feller (1989) found that nitrate-N in stream water increased from clearcutting (approximately 10 kg/ha), to clearcutting plus slashburning (approximately 20 kg/ha), to herbicide application in young plantations (approximately 40 kg/ha) in Coastal Western Hemlock (CWH) biogeoclimatic zone forests in southwestern British Columbia. Herbicides such as glyphosate can chelate heavy metals, such as copper

FIGURE 12.10 *The characteristics of forest harvesting, soil properties, and the rate of re-vegetation following harvesting can have a strong influence on chemical loading in a watershed. (Photo: R.G. Pike)*

and aluminum, and displace anions, such as phosphate, from the soil exchange complex, which can cause increased leaching of these nutrients (Barrett and McBride 2006).

In Finland, leaching of nitrogen and phosphorus through the soil was greater in mechanically mounded areas than beneath furrows. This was because less organic material occurred in the furrows, and chemical fluxes in mineral soil leachate were increased by mounding compared to clearcutting with no site preparation (Piirainen et al. 2007); however, in Finland, ditching and mechanical scarification caused no increase in chemicals in stream water compared to clearcutting alone (Ahtiainen and Huttunen 1999). Hart et al. (1981) found that the overall amount of leaching from a windrow and burn treatment was similar to that from a broadcast burn treatment; the increased leaching from beneath windrows compensated for the decreased leaching between windrows. Feller and Hamilton (1994) found greater cation and nitrogen levels in mineral soil leachate after clearcutting and mechanical scarification in Engelmann Spruce–Subalpine Fir forests than after clearcutting alone.

Generally, the more rapidly an area re-vegetates after harvesting, the more rapidly stream nutrient loading returns to pre-harvest levels. If vigorous re-vegetation results in greater nutrient immobilization rates than occurred before harvesting, nutrient fluxes to freshwater can decline to below pre-harvesting levels (Feller 2005). Partial cut or variable retention silvicultural systems remove less vegetation than clearcutting; therefore, the magnitude of the impact on stream chemistry will be less than clearcutting, and the duration of the effects may also be less (Gundersen et al. 2006; Stednick [editor] 2008). Generally, the greater the ability of a forest soil to retain nutrients, the lower the amount of nutrients that will be leached from the soil into a water body.

Selected case studies

Public concern has been expressed about the effects of forest harvesting on stream water quality (e.g., MacDonald and Stednick 2003). For example, high concentrations of nitrate can have adverse effects on human health. However, no study in North America has shown that forest harvesting (even clearcutting followed by slashburning) increases stream water nitrate concentrations above permissible levels for drinking water (Brown and Binkley 1994; Binkley et al. 2004;). Although forest harvesting can increase

FIGURE 12.11 *The maintenance of streamside buffers is one strategy to help prevent changes in water quality following forest harvesting. (Photo: J.D. Stednick)*

stream water nitrate levels, exceeding water quality guidelines would likely occur only in areas where the background ecosystem nitrogen levels are already high because of higher atmospheric inputs from anthropogenic sources or in areas dominated by nitrogen-fixing vegetation species, such as red alder growing in riparian zones.

Most published studies reported minimal to modest changes in water chemistry due to timber harvesting. Removal of woody debris after harvesting can decrease the magnitude of chemical loading unless the removal causes substantial site disturbance, which can increase chemical loading (Feller and Hamilton 1994; Staaf and Olsson 1994; Strahm et al. 2005; Belleau et al. 2006).

In the Alsea watershed study near Newport, Oregon, Brown et al. (1973) observed no significant changes in nitrate-N or phosphorus concentrations after logging when streamside buffers were maintained. Tiedemann et al. (1988) analyzed the effects of various harvesting methods (uncut, 41% clearcut, 17% clearcut, and selection) in four catchments in the Blue Mountains of eastern Oregon. Minimal increases in nitrate-N concentration occurred in clearcut treatments and peaked at 0.52 mg/L (increased nitrogen outputs were balanced by inputs through precipitation), whereas dissolved phosphate-P increased in the 41% clearcut treatment (Tiedemann et al. 1988).

Murray et al. (2000) examined the long-term effects of partial harvesting in two watersheds (7 and 33% of watershed) on the western Olympic Peninsula, in Washington. In this study, partial harvesting had little influence on stream chemistry 11–15 years after harvesting. Higher nitrate concentrations in the harvested areas were attributed to the presence of red alder. Similar findings were recorded at the Alsea watershed experiment 25 years after harvesting (Stednick [editor] 2008).

Adams and Stack (1989) examined several harvesting methods in four watersheds on the west slopes of the Cascade Range at Coyote Creek, Oregon. The treatments studied included uncut, shelterwood (50% area removed), patch cut (30% removed), and clearcut. Clearcutting had the largest influence on water quality, whereas shelterwood and patch cut showed very little effect. Nitrate yields in the clearcut were highest in the third year following harvest (2.9 kg/ha), with a peak concentration of 510 μg/L recorded in the fourth year after harvesting. Differences among all four watersheds were negligible after 9 years.

Harr and Fredriksen (1988) studied the effects of logging on water quality in the Bull Run watershed in Oregon. They assessed three different treatments: (1) uncut, (2) clearcut, and (3) clearcut and broadcast burned. Both clearcut treatments had essentially no streamside buffers. Nitrate-N concentrations increased sixfold in the clearcut treatment for 7 years after harvesting, with values frequently exceeding 100 μg/L during the high-flow period (Harr and Fredriksen 1988). Nitrate-N concentrations in the burned clearcut treatment increased fourfold for 6 years after harvesting, but values rarely exceeded 50 μg/L during the high-flow period. No other water quality changes were detected.

The forest harvesting effects on water quality recorded in Washington and Oregon are consistent with those observed in British Columbia. Hetherington (1976) monitored the effects of harvesting on the chemical water quality of a small watershed (Dennis Creek) near Penticton. Harvesting resulted in a significant increase in water colour, and minor increases in K^+, Na^+, Cl^-, electrical conductivity, total organic carbon, and dissolved solids. Following harvesting, all parameters, except colour, were within drinking-water standards (Hetherington 1976).

Scrivener (1988) summarized the changes in concentrations of dissolved ions recorded during the Carnation Creek study in coastal British Columbia. Increases in conductivity occurred 1 year after logging and slashburning, but on average, returned to pre-logged conditions 2 years after logging was completed. Nitrate concentrations effectively doubled at Carnation Creek 1 year after logging began. Increased concentrations were of short duration and persisted for only 2 years at low flows and 7 years at high flows after harvesting activities ended (Scrivener 1988).

In studying the long-term effects of forest harvesting on a small, southern Vancouver Island coastal lake, Nordin et al. (2007) reported increased concentrations of Ca^{2+}, Cl^-, Mg^{2+}, Na^+, specific conductance, nitrate, and ammonia/ammonium in the lake water after logging. For most constituents, peak concentrations occurred 2–3 years after logging, and most ions returned to background concentrations after 5–8 years. Nordin et al. (2007) also reported that the largest increases in constituents were for nitrate and ammonia, with a decreasing trend for phosphorus, which indicated no obvious response to logging.

Forest Management and Dissolved Oxygen

Declines in stream water dissolved oxygen concentrations during the summer following forest harvesting have sometimes been significant and resulted in values below the Canadian guidelines of 6.5 mg/L for cold water (Plamondon et al. 1982; Brown 1985). Forest harvesting can alter stream water dissolved oxygen concentrations primarily by affecting solubility, depletion rates, and re-supply rates, and by creating barriers to oxygen movement.

Forest harvesting has no effect on atmospheric pressure but can affect both stream temperature and dissolved ions. Changes in dissolved ions are usually small; therefore, water temperature becomes the most important determinant of oxygen solubility (Brown 1985; Hanson et al. 2006). When forest harvesting increases stream temperatures, declines in dissolved oxygen concentrations are proportional to the degree of increase in stream water temperature.

Deposition of organic material into streams may increase chemical and biological oxygen demands, leading to declines in dissolved oxygen levels (Servizi et al. 1971; Moring 1975; Schreiber and Duffy 1982; Brown 1985). This may be exacerbated when water velocities are reduced, as in pools or areas where water is impounded by organic materials and where organic matter loads are high (Krammes and Burns 1973; Plamondon et al. 1982; Naiman 1983). In one study, Servizi et al. (1971) determined that stream water dissolved oxygen was a balance between stream velocity, temperature, and concentrations of tree bark in the stream.

If forest harvesting removes a water body's protective canopy cover, increased exposure to the atmosphere in winter could theoretically lead to increased ice cover and decreased mixing of oxygen-containing air with the water beneath the ice (e.g., Whitfield and McNaughton 1986); however, this effect does not appear to be documented in the literature. More important is the influence of forest harvesting on sediment levels in water and deposition of this sediment onto streambeds, which prevents the movement of oxygen in the surface waters into the streambed (Scrivener and Brownlee 1982; Whitman and Clark 1982; Everest et al. 1987).

Wildfire, Prescribed Fire, and Water Chemistry

In British Columbia, some wildfires have led to severe surface erosion, debris flows, and flooding (Curran et al. 2006; see also Chapter 19, "Climate Change Effects on Watershed Processes in British Columbia"). The specific effect of fire on hydrologic and geomorphic processes has been discussed in detail in many other references (see Moore et al. 2008b) and chapters of this Compendium. Specifically, the reader is referred to the following information.

- Formation of water-repellent, or hydrophobic, soil properties (Chapters 6 and 8)
- Effects of fire on snow accumulation, snow ablation, and interception processes (Chapter 7)
- Influence of fire on streamflow duration (Chapter 6)
- Effects of fire on peak flows (Chapter 7)
- Fire-generated erosion and landslides (Chapter 8)
- Rehabilitating wildfire-affected areas (Chapter 18)
- Climate change and effects of frequency of disturbances (fire) (Chapter 19)
- Modelling future frequency/magnitude of forest disturbances (Chapter 19)

Some wildfires can cause severe changes in soil and vegetation, which can affect hydrology and slope stability (Scott and Pike 2003). A common concern is the formation of a water-repellent layer below the soil surface that results from the deposition of hydrophobic compounds, leading to a reduction in water infiltration (see Chapter 6, "Hydrologic Processes and Watershed Response," and Chapter 8, "Hillslope Processes"). These changes can cause overland flow, especially during high-intensity rainfall under dry soil conditions (Chapter 8) leading to increased runoff and sediment input to water bodies. Additionally, the loss of the protective vegetation and organic soil layer can increase the likelihood of splash erosion of exposed mineral soil (see Chapter 8). Fire also has the potential to increase stream temperatures through the reduction of shading vegetation in riparian areas (Leach and Moore 2010) and the widening of the channel because of the loss of channel bank strength (Eaton et al., 2010).

Following wildfire, the potential effects on water quality include increased sediment inputs and stream temperatures (Bladon and Redding 2009), flooding, and other water chemistry changes. The balance of this discussion will be on the effects of fire on water chemistry. Both wildfire and prescribed burning have been shown to have similar effects on stream chemistry as does forest harvesting. Many studies have reported increased nutrient movement through soils and into streams following fire (Tiedemann et al. 1979; DeBano et al. 1998; Minshall et al.

2001; Bêche et al. 2005; Murphy et al. 2006; Bladon et al. 2008). Fire effects and forest harvesting effects are influenced by similar factors. For example, the extent of nutrient movement into streams following fire depends on the buffering capacity of soils (McColl and Grigal 1977; DeBano et al. 1998), proportion of a watershed burned (Carignan et al. 2000; Bêche et al. 2005), rate of regrowth of vegetation (Clinton et al. 2003), streamflow generation mechanisms (Huffman et al. 2001; Kunze and Stednick 2006), and streamflow regime (Bladon et al. 2008).

An important factor that influences fire effects on stream chemistry is fire behaviour (Figure 12.12). Fires that consume more organic material generally have a greater effect on water quality than fires that consume less (Boerner and Forman 1982; Nakane et al. 1983; Bayley et al. 1992; Belillas and Feller 1998; DeBano et al. 1998; Malmer 2004). The seasonal timing of fire events is also important. Fall and spring burns can have different effects on water quality depending on soil moisture content and the amount of nutrient uptake by the surviving vegetation.

FIGURE 12.12 *Fires that consume more organic material generally have a greater effect on water quality. (Photo: P.J. Tschaplinski)*

Fire could be expected to cause a greater duration and magnitude of water quality effects than forest harvesting partly because of the greater loss (death) of vegetative cover, and the conversion of insoluble chemicals within organic matter into readily soluble chemicals in ash, which are more quickly and easily transported into streams (Stednick 2010); however, there are many confounding factors. For example, net nitrification in the soil may be greater after harvesting than after fire. This may happen if nitrifying bacteria are more adversely affected by fire or if greater immobilization of nitrate occurs in the soil after a fire (LeDuc and Rothstein 2007), in which case less nitrate could be expected to leach into streams. Fire often enhances nitrification (Mroz et al. 1980; Jurgensen et al. 1981; Herman and Rundel 1989; DeBano et al. 1998) because of the increased ammonium levels, stimulation of nitrifying bacteria or fungi, or sorption by charcoal of nitrification-inhibiting phenolics (DeBano et al. 1998; DeLuca et al. 2006). The charred material left by fire can be a chemically active heterogeneous mixture of compounds containing nitrogen, sulphur, and oxygen functional groups, which can be quickly oxidized, attacked by microbes, and rendered soluble (Knicker 2007), thereby facilitating nitrate and sulphate additions to streams. Furthermore, dissolution of smoke gases directly into streams may also enhance stream water nitrate levels. Spencer and Hauer (1991) reported that dissolution of smoke gases into freshwater would yield relatively more nitrate for a well-ventilated fire, and relatively more ammonium for an incomplete combustion or poorly ventilated fire. In general, slashburning and clearcutting are associated with greater chemical constituent flow through soil and streams than clearcutting alone (Hart et al. 1981; Feller and Kimmins 1984; Tiedemann et al. 1988).

Some of the reported effects of prescribed fire in logging slash are confounded by the effects of forest harvesting. In the Alsea watershed study, nitrate-N increased from 0.70 to 2.10 mg/L on a clearcut and broadcast-burned basin but returned to pre-logging levels after 6 years, whereas the patch-cut treatment showed no associated changes in water quality (Brown et al. 1973). Martin and Harr (1989) studied nutrient changes related to harvesting and broadcast burning of two mature Douglas-fir forested watersheds in the H.J. Andrews Experimental Forest. In their study, clearcutting and shelterwood harvesting in combination with broadcast burning did not increase net losses of nutrients from the study sites. However, stream water nitrate-N levels did increase

30-fold after harvesting, although this level was still less than half of the nitrogen input from precipitation.

Feller and Kimmins (1984) separated burning and harvesting effects by monitoring stream water chemistry for 2 years before and 9 years after clearcut logging of two small basins near Haney. During logging, streams in both watersheds were avoided, and a combination of tractor and cable yarding was used for timber extraction. Both watersheds possessed minimal roads and one of the treatment watersheds was broadcast burned. In general, all constituents increased for 2–3 years following harvest and then declined below pre-harvest values. The largest increases occurred in potassium and nitrate. Clearcutting and burning resulted in greater nutrient losses than clearcutting alone (1293 kg N/ha vs. 245 kg N/ha for the first 2 years after harvesting), although most of the difference was due to losses to the atmosphere during burning. Subsequent work by Feller (1989) indicated that slashburning doubled the increased stream water nitrate output compared to clearcutting alone.

For 3 years, Carignan et al. (2000) monitored nutrient changes in 38 thermally stratified Boreal Shield lakes located in catchments that were subjected to forest harvesting and wildfire. Dissolved organic carbon and light attenuation was 3 times higher in lakes within harvested catchment areas than in lakes in control catchments. Lakes in the treatment catchments contained 2–3 times higher concentrations of total phosphorus, 2 times higher total organic nitrogen concentrations, and up to 6 times higher levels of K^+, Cl^-, and Ca^{2+} than lakes in the control catchments. Nitrate concentrations were up to 60 times higher in lakes in burned catchments than in those in harvested and control catchments. Carignan et al. (2000) stated that the chemical changes observed were directly proportional to the area disturbed (cut/burned) divided by the lake volume/area. Although increased levels of nitrogen and phosphorus export from the forest were negligible, Lamontagne et al. (2000) reported that it was an important supplementary source of nutrients for the study lakes. In northern Alberta, McEachern et al. (2000) studied forest fire–induced effects on nutrient concentrations in 29 boreal sub-Arctic lakes for 2 years following wildfire. Lakes in burned catchments had 2 times higher concentrations of total phosphorus, total dissolved phosphorus, and soluble reactive phosphorus; 1.5 times higher dissolved organic carbon concentrations; and 1.2 times higher concentrations of total and total dissolved nitrogen, nitrate+nitrite, and ammonium than lakes in unburned catchments.

An important difference between forest harvesting and fire is that both phosphate and sulphate fluxes in streams are often greater following fire (Gluns and Toews 1989; Spencer and Hauer 1991; Williams and Melack 1997; DeBano et al. 1998; Earl and Blinn 2003), whereas these fluxes are usually unaffected, or reduced in the case of sulphate, following forest harvesting. This can be attributed to the leaching of relatively large amounts of phosphate and sulphate from the ash left by fires (Figure 12.13).

Studies on the effects of forest fires on stream water dissolved oxygen are scarce. Earl and Blinn (2003) found that dissolved oxygen levels in streams in New Mexico declined following wildfires. Feller (unpublished data) found that clearcutting and slashburning in the CWH zone in southwestern British Columbia caused greater declines in stream water dissolved oxygen in the summer than clearcutting alone. This effect was expected, as fire increased summer stream temperatures to a greater extent than did clearcutting alone (Feller 1981). Consequently, fire can potentially cause declines in stream water dissolved oxygen, depending on its effect on stream temperature and organic material in streams.

Fire Retardants and Water Chemistry

Forest fire suppression often involves the aerial application of fire retardants. These are primarily ammonium phosphate– or sulphate-based compounds with small amounts of other chemicals used as dyes, for anti-corrosion, or for other purposes. Fire suppressants are generally applied as foams that are made of proprietary mixtures of sodium and ammonium salts, alcohol, ether, and sulphates. Relatively few studies have assessed the effects of fire retardants on freshwater; even fewer have assessed the effects of fire suppressants. The major factors that influence the effects of fire retardants on freshwater chemistry have not all been quantified, but based on an analogy of herbicide applications, which have been studied (see "Herbicide chemicals" below), these factors are likely to include:

FIGURE 12.13 *Both phosphate and sulphate fluxes in streams are often greater following fire due to leaching from ash. (Photo: J.D. Stednick)*

- location of the application in relation to the water body;
- retardant type;
- quantity applied;
- application method;
- weather at the time of application;
- weather following the application;
- season of application;
- soil characteristics;
- ability of the aquatic ecosystem to utilize the added retardant chemicals; and
- ability of the water body to dilute the retardant chemicals (e.g., volume, discharge of the water body).

Fire retardants applied close to a water body have been shown to increase stream water ammonium, phosphate, and nitrate concentrations (Norris and Moore 1981; Norris and Webb 1989; Dissmeyer [editor] 2000). These increases are usually short lived (< 1 hour initially) but may re-occur in response to subsequent streamflow-generating rainfall events (Stednick 2000). High phosphate concentrations in streams following retardant application may be a concern from the viewpoint of downstream eutrophication. A useful summary of the ecological effects of firefighting foams and retardants can be obtained from Adams and Simmons (1999).

Some fire retardants contain sodium ferrocyanide as a corrosion inhibitor (Norris et al. 1983). In the presence of UV radiation, the ferrocyanide decomposes, yielding cyanide ions that react in acidic solutions and produce the highly toxic hydrogen cyanide. Norris et al. (1983) estimated that toxic concentrations of cyanide are unlikely following application of ferrocyanide-containing retardants, but more recent work by Little and Calfee (2002) suggested that toxic concentrations can occur, particularly when light levels are high and soils adjacent to streams are coarse textured and contain little organic matter.

Insects, Tree Diseases, and Water Chemistry

Insect infestations that kill trees can have a similar effect on water and chemical constituent flow through forested watersheds as forest harvesting (Figure 12.14). Studies on insect effects on freshwater, particularly on its chemistry, are relatively scarce. The few published studies available have all reported increases in nitrate leaching through soil or in streams following insect-caused tree mortality, even with as little as 20% basal area affected (Swank et al. 1981; Douglass and Van Lear 1983; Webb et al. 1995; Eshleman et al. 1998; Huber 2005; Lewis and Likens 2007). Stream water and soil leachate nitrate

FIGURE 12.14 *Changes in forest cover as a result of insect infestations in British Columbia, such as the mountain pine beetle, can have an important effect on water quantity and quality. (Photo: R.G. Pike)*

levels can remain elevated for extended periods—for at least 7 years after a severe bark beetle infestation of spruce in Germany (Huber 2005) and 5 years after defoliation of mixed hardwood-conifer forests in the northeastern United States (Lewis and Likens 2007). This duration is longer than usually occurs after forest harvesting, but peak concentrations were below water quality guidelines. Lewis and Likens (2007) also found elevated cation and decreased sulphate concentrations in stream water, identical to trends following forest harvesting.

Even fewer studies have looked at the effects of tree disease outbreaks on stream water chemistry, and none of these was conducted in Canada. Hobara et al. (2001) found elevated stream water nitrate concentrations and Tokuchi et al. (2004) found elevated stream water nitrate, magnesium, and calcium concentrations and reduced sulphate concentrations following tree mortality from a pine wilt disease in Japan. Again, these influences on stream water chemistry are similar to those following forest harvesting. No studies have looked at the influence of insects and pathogens on stream water dissolved oxygen levels, although it can be inferred that any disturbance adding organic matter (e.g., litter from dying trees) to a stream or exposing a stream to increased solar radiation following tree mortality would have similar effects as forest harvesting.

Herbicides and Water Chemistry

Herbicides may affect stream water chemistry, both through nutrient loading and the loading of the herbicide chemicals themselves. Studies that have looked at herbicide application effects on stream water dissolved oxygen levels and resulting effects on aquatic life appear to be lacking.

Nutrients

Herbicide applications can cause greater increases in nutrient chemical concentrations in streams than forest harvesting, especially if buffers along riparian areas are not used. Nitrate concentrations increased to relatively high levels in stream water following repeated herbicide applications in a New Hampshire forested watershed (Likens et al. 1970) and in a California chaparral watershed (Davis 1987). Repeated herbicide applications are uncommon in typical forest management practices but have been used to illustrate nutrient cycling processes. Large increases in stream water nitrate concentrations have been attributed to increased nitrification rates in the soil following herbicide application (Likens et al. 1969; Davis 1987), but this does not always happen (Stratton 1990). Nitrification may depend on the relative abundance of nitrifying organisms in the ecosystem, the degree of impact of the herbicide, the increase in moisture and light reaching the soil surface, or the type of herbicide used. Consequently, different herbicides will have different effects on nitrification (Guenzi [editor] 1974). This suggests that the type of herbicide used is another important factor influencing the effects of herbicides on stream water nutrient chemistry.

In several studies, stream water nitrate concentrations increased following herbicide applications (Likens et al. 1970; Sollins et al. 1981; Neary et al. 1986; Davis 1987; Feller 1989; Simpson et al. 1997). Other nutrient chemical concentrations also increased, whereas sulphate concentrations decreased following herbicide application (Likens et al. 1970). Intervals between herbicide applications that are sufficiently long enough to allow vegetation to recover, such as 5–6 years in the CWH biogeoclimatic zone, may minimize increases in nitrate concentration to only moderate levels (M.C. Feller, unpublished data). These trends are generally the same as those following forest harvesting, suggesting that the factors controlling stream water nutrient chemistry response to forest harvesting also control the response to herbicides.

Herbicide chemicals

The movement of herbicide chemicals and their degradation products into freshwater ecosystems has been relatively well studied and reviewed (Brown 1978, 1985; Leonard 1988; Norris et al. 1991; Dissmeyer [editor] 2000; Michael 2000). The main factors influencing the amount of herbicide that enters a water body are the same as those for fire retardants. The potential for herbicide drift into water bodies is greater for aerial than ground applications, particularly if it is windy at the time of application. Herbicide chemicals are more likely to enter water bodies if these substances are soluble (although the fat-soluble–water-insoluble herbicides are generally more deleterious than the water-soluble ones), do not degrade quickly, do not volatilize easily, and are not easily sorbed by soils. The closer the application to a water body and the greater the quantity of herbicide used, the greater the likelihood that the herbicide will enter the water body. Direct application, chemical drift, and overland flow (including flow in ephemeral channels) are the main flow pathways by which herbicide chemicals enter water bodies and subsequently affect water quality.

Herbicide concentrations in surface waters have sometimes exceeded permissible levels, but high concentrations tend to be short lived and generally occur soon after application, although concentrations often increase during rainfall events that occur in the first few months after application (Norris et al. 1983; Wan 1983, 1986; Brown 1985; Leitch and Fagg 1985; Neary et al. 1986; Michael et al. 1989; Michael 2000). Heavy rain shortly after application can result in relatively high concentrations of herbicides in stream water if flow occurs either overland (e.g., roads) or in ephemeral channels (Brown 1978, 1985; Norris et al. 1983; Wan 1983; Leonard 1988). In two studies in coastal British Columbia and Oregon, herbicide levels in streams flowing through treated areas were shown to be elevated close to, but not beyond, permissible levels (Wan 1983; Newton et al. 1984). Large buffer strips and an aerial application of a relatively small quantity of glyphosate in the Interior Cedar–Hemlock zone in British Columbia resulted in undetectable levels of the herbicide in stream water (Gluns 1989). A useful synthesis of Carnation Creek herbicide research can be found in Reynolds et al. (1993).

Fertilizer and Water Chemistry

Forest stands are commonly fertilized to increase stand volume and reduce rotation length. Some lakes, reservoirs, and streams in British Columbia are fertilized to increase primary productivity and the growth rates of fish (Stockner and Shortreed 1978, 1985; Perrin et al. 1984; Johnston et al. 1990; Pike and Perrin 2005). The added nutrients increase growth rates of algae, which increases food availability for zooplankton (in lakes) or benthic invertebrates (in streams and lakes). This, in turn, increases food availability for fish, yielding greater growth rates and survival (Pike and Perrin 2005). A comprehensive review of the use of fertilizer for both forestry and fisheries applications can be found in Pike and Perrin (2005).

Numerous reviews have described the potential effects of forest fertilization on water quality and biological production in aquatic ecosystems (e.g., Fredriksen et al. 1975; Moore 1975; Bisson et al. 1992; Binkley and Brown 1993; Perrin 1994; Binkley et al. 1999a, 1999b; Dissmeyer [editor] 2000; Anderson 2001; Pike and Perrin 2005). Water quality concerns are mostly related to unintentional increases in concentrations of urea, nitrate, ammonia/ammonium, phosphorus, sulphur, and heavy metals.

In forestry applications, urea fertilizer (the most common fertilizer used) in the presence of moisture is hydrolyzed to yield ammonia and then ammonium, which is effectively retained on soil cation exchange sites. Ammonium is actively taken up and used as a nitrogen source by trees (Perrin 1994). Ammonium is also nitrified in the presence of autotrophic bacteria in the soil to form nitrate. This nitrate is taken up and used as a nitrogen source by trees, but it is relatively mobile in forest soils and can be lost to streams more so than ammonium (Pike and Perrin 2005).

In several case studies, most forest fertilizer applications resulted in short-term increases in nitrogen (e.g., nitrate–N) concentrations in streams. When leave strips or buffers were used around water bodies, relatively low peak concentrations of nitrate–N and ammonium–N were recorded in the water bodies. Concentrations of total ammonia–N generally remained above background concentrations for several weeks to months after treatment, whereas nitrate–N concentrations remained above background for several months to a year after treatment (Perrin 1994).

Because of the many controlling factors, the response of stream water nitrogen concentrations to fertilization has been quite variable (Table 12.6); however, the general consensus is that fertilization is not likely to have adverse effects on water quality (Bisson et al. 1992; Binkley et al. 1999a, 1999b; Pike and Perrin 2005).

Although no published water quality guidelines are available for urea–N, concentrations of several thousand milligrams per litre are required for toxic effects, which would be much higher than what might reasonably occur in any stream environment (Binkley et al. 1999a). However, in southwestern British Columbia, Hetherington (1985) found that stream water nitrate-N concentrations closely approached permissible levels following urea fertilization in areas where streamside buffers were not applied (Tables 12.6 and 12.7).

Few studies have looked at fertilizer applications on stream water dissolved oxygen levels. In one study, no effects were found following urea fertilization of a boreal forest in Quebec (Gonzalez and Plamondon 1978).

The addition of phosphorus to lakes and streams is typically done with very tight controls on specific phosphorus loadings because the element is often the primary nutrient that limits aquatic biological production. Excess phosphate in water bodies can cause eutrophication, with subsequent death and decay of aquatic plants and algae, which leads to the depletion of dissolved oxygen. Phosphorus fertilizers have sometimes caused large increases in stream water phosphorus levels. In New Zealand, peaks of 50 mg/L of phosphate-P were recorded and concentrations exceeded 0.1 mg/L for many weeks following application of phosphorus fertilizers (Neary and Leonard 1978). In review of forest fertilization trials in coastal British Columbia, Perrin (1994) found that low-level phosphorus concentrations commonly dropped to background levels within 120 days of fertilizer application, and likely resulted in some increased productivity over 4 months (Table 12.8). Stream water phosphorus concentrations are influenced by the time-release factor of the fertilizer; higher concentrations are likely to occur with fast-release rather than slow-release fertilizers (Sharpley and Syers 1983). Fertilizers also induce leaching of other chemicals into streams, particularly potassium, sodium, magnesium, and calcium (Gonzalez and Plamondon 1978; Lundin and Bergquist 1985; Edwards et al. 1991; Briggs et al. 2000); however, the increases in these chemicals have generally been slight and short lived (< 1 year).

TABLE 12.6 *Peak nitrate-N and total ammonia-N concentrations from British Columbia case studies (Pike and Perrin 2005)*

Location	Treatment level (kg N/ha)	Fertilizer -free buffer width (m)	Nitrate–N control (mg/L)[c]	Peak nitrate–N concentration (mg/L)	Duration of elevated nitrate–N levels(days)[d]	Total ammonia –N (NH_4^+ + NH_3–N control (mg/L)[c]	Peak total ammonia–N (NH_4^+ + NH_3–N) (mg/L)	Duration of elevated ammonia levels (days)[d]	References
Sayward Forest[a]	200	None	0.001	0.34	111	< 0.004	3.36	111	Perrin et al. 1984
Sayward Forest[b]	200	50	0.001	0.19	100	< 0.004	0.243	142	Perrin et al. 1984
Lens Creek	224	None	0.028–0.151	9.3	435	0.08	1.9	13	Hetherington 1985
Gold Creek	176 with 52 kg S/ha	20	—	0.04	—	0.005–0.010	0.013	—	MacDonald 1987
Keogh River tributary	200	None	0.01–0.08	0.120	14	0.01–0.015	4.6	113	Perrin 1987a
Gold River	200	30	0.02–0.07	0.28	73	0.011–0.017	0.03	3	Perrin 1987b
Slesse Creek	200	10	0.21–0.33	0.21–0.33	na	0.020	0.024	2	Perrin and Bernard 1988
Glerup Creek	200	10	< 0.01	0.047	> 39	< 0.01	0.57	31	Perrin 1989
Glerup Creek	200	None	< 0.01	0.301	96	< 0.01	3.69	31	Perrin 1989
Qualicum River	200	30	0.035	0.088	136	< 0.005	< 0.005	na	Perrin 1990a
Rosewall Creek	200	30	0.005–0.035	0.057	136	< 0.005	< 0.005	na	Perrin 1990a
Mashiter Creek	200	50	0.005–0.01	0.037	47	< 0.005	< 0.005	na	Perrin 1990b
Tarundl Creek	200	30	0.03–0.130	0.03–0.130	na	< 0.005	0.160	29	Perrin 1991
Honna River	200	30	0.022–0.097	0.022–0.097	na	0.01–0.02	0.042	9	Perrin 1991
Honna River tributary	200	None	< 0.005	0.130	> 97	< 0.005	0.471	61	Perrin 1991
Nusatsum River	200	None	0.005–0.035	0.088	> 108	< 0.005	< 0.005	na	Perrin 1992
Sallompt River	200	30	0.12–0.17	0.21	>141	< 0.005	< 0.005	na	Perrin 1992

a Data are the maximum concentration from six replicate streams; no streams were affected by fertilizer spills.
b Data are the maximum concentrations from four replicate streams.
c Data are from sample sites not affected by fertilization and indicate concentrations at the time that peak concentrations were measured at the treatment site.
d Number of days from time of fertilization to return to control values.

TABLE 12.7 *Peak urea-N concentrations from British Columbia case studies (Pike and Perrin 2005)*

Location	Urea Treatment level (kg N/ha)	Fertilizer-free buffer width (m)	Urea–N control (mg/L)[a]	Peak urea–N concentration (mg/L)	Duration of elevated urea levels (days)[b]	References
Sayward Forest[c]	200	None	< 0.005	49.3	141	Perrin et al. 1984
Sayward Forest[d]	200	50	< 0.005	0.658	136	Perrin et al. 1984
Lens Creek	224	None	0.03	14.0	7	Hetherington 1985
Nusatsum River	200	None	0.005–0.018	0.005–0.018	na	Perrin 1992
Sallompt River	200	30	0.005–0.018	0.005–0.018	na	Perrin 1992
Tarundl Creek	200	30	< 0.01	0.614	66	Perrin 1991
Honna River	200	30	0.005–0.020	0.296	10	Perrin 1991
Honna River tributary	200	none	0.005–0.055	2.43	91	Perrin 1991

a Data are from sample sites not affected by fertilization and indicate concentrations at the time that peak concentrations were measured at the treatment site.
b Number of days from time of fertilization to return to control values.
c Data are the maximum concentration from six replicate streams; no streams were affected by fertilizer spills.
d Data are the maximum concentrations from four replicate streams.

TABLE 12.8 *Peak soluble reactive phosphorus concentrations from British Columbia case studies (Pike and Perrin 2005)*

Location	Treatment level (kg P/ha)	Fertilizer-free buffer width (m)	Soluble reactive phosphorus control (mg/L)[a]	Peak soluble reactive phosphorus concentration (mg/L)	Duration of elevated soluble reactive phosphorus (days)[b]	References
Keogh River tributary	100	None	< 0.001	10.6	120	Perrin 1994
Glerup Creek	100	None	< 0.001	1.92	73	Perrin 1989
Glerup Creek	100	10	< 0.001	0.560	73	Perrin 1989

a Data are from sample sites not affected by fertilization and indicate concentrations at the time that peak concentrations were measured at the treatment site.
b Number of days from time of fertilization to return to control values.

SUMMARY

This chapter summarizes the interactions of chemical, physical, and biological processes that control water quality in British Columbia. It also provides an overview of the generalized effects of forest management and other disturbances, including forest harvesting, wild and prescribed fire, insects and tree diseases, and applications of chemical fire retardants, herbicides, and fertilizers on water quality. The effects on water chemistry are varied and are a function of the type and level of activity or disturbance, the terrestrial or aquatic ecosystem affected, the water quality constituents considered, and weather conditions.

Most published studies reported small to moderate chemical changes as a result of forest harvesting. Although harvesting can possibly increase stream water nitrate levels, exceeding water quality guidelines would likely occur only in areas where the background ecosystem nitrogen levels were already high. Changes in freshwater chemical loading (particularly for nitrogen) caused by forest harvesting are normally short lived—up to 7 years but usually considerably less; however, base cation changes may occur for more than 10 years. Wildfire, insects, and tree diseases have similar effects on water chemistry as forest harvesting. Yet wildfire can be expected to cause a greater duration and magnitude of effects than forest harvesting because more vegetative cover can be lost and insoluble chemicals within organic matter converted into readily soluble chemicals in ash, which are more quickly and easily transported into streams. Forest harvesting followed by prescribed burning has a greater effect on freshwater chemistry than does forest harvesting alone. Fertilizer applications to forests may temporarily increase nitrogen concentrations in freshwater, especially if fertilizer-free application areas are not used. Fertilization with urea has not been shown to impair drinking water quality. Herbicide concentrations in surface waters have sometimes exceeded permissible levels, but high concentrations tend to be short lived and generally occur soon after application. Deforestation with herbicides is likely to cause greater chemical changes in freshwater as compared to other disturbances.

This chapter began by defining water quality as the chemical, physical, and biological characteristics of water with respect to its suitability for a particular use. It is important to re-emphasize that water quality varies in space and time and that any water quality response can be immediate or manifest over the long term. Consequently, water quality monitoring and sampling programs must be designed to account for this variability and the complex effect multiple disturbances can have on sampled water quality.

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Stream and Riparian Ecology

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INTRODUCTION

Water is a valuable resource for humans (direct consumption, power, irrigation, industry) and provides essential habitat for many organisms, including highly valued fish species such as salmonids. Aquatic habitat is influenced by processes active not only in the near-stream (riparian) zone (e.g., provision of shade) but also over the entire watershed (e.g., hillslope hydrologic processes that control the supply of water or the generation of landslides). Processes at both of these scales, and others, can be profoundly influenced by forestry activities, as described in more detail in Chapter 7 ("The Effects of Forest Disturbance on Hydrologic Processes and Watershed Response"), Chapter 9 ("Forest Management Effects on Hillslope Processes"), and Chapter 10 ("Channel Geomorphology: Fluvial Forms, Processes, and Forest Management Effects").

The purpose of this chapter is to provide an overview of stream and riparian ecology in British Columbia. It describes the ecological structure and function of streams and the associated riparian zones, and the interactions between them. Several topics in this chapter are integrative; therefore, some topics are addressed only briefly but references are provided for more in-depth coverage. For additional information on stream and riparian ecology, see Giller and Malmqvist (1998), Naiman and Bilby (editors, 1998), Naiman et al. (2005), Allan and Castillo (2007), and Richardson and Danehy (2007).

STREAMS

Definitions

The word "stream" is a generic term used to describe watercourses of all sizes that have channels of running water and which show evidence of fluvial processes, even if it is only the erosion of organic materials during peak runoff events. The term "river" is generally used to describe a large stream (e.g., Richardson and Milner 2005). No specific scale distinguishes a river from a stream, creek, or brook; hence, the term stream is used to mean all running waters. Stream channels include the active channel (or open channel), as well as relict channels that may be disconnected from the active channel or are connected only at high flow. The active channel is characterized by open water interacting with its bed materials (mineral substrate, wood). Below and adjacent to the active channel is the hyporheic zone—a zone of saturated sediments where infiltration of stream water via the streambed and banks has a strong influence on water quality. It is typically the interface between stream water and groundwater and, as such, is often characterized as an ecotone spanning the boundaries of the surface and subsurface environments. The riparian zone is the terrestrial area adjacent to the stream. It is influenced by the water in the stream and (or) has an influence on the aquatic system (see below). A more comprehensive discussion of the classification of streams, channel types, and morphology, and the processes that shape stream environments is provided in Chapter 10 ("Channel Geomorphology: Fluvial Forms, Processes, and Forest Management Effects").

The duration of surface flow throughout the year in a given stream will vary from year to year, depending on weather patterns. It will also vary among streams, and along streams, with smaller streams more likely to have lower flow duration than bigger streams. In perennial streams, flow over the streambed is usually maintained throughout the year, although the entire active channel does not have to be inundated (Feminella 1996). In general, perennial streams are considered distinct from intermittent and ephemeral streams along a continuum of flow duration (Feminella 1996; Halwas et al. 2005). Intermittent and ephemeral channels differ in the duration of surface flow. Intermittent channels carry water through an extended portion of the year and may support populations of some benthic invertebrates with adaptations to this environment. Ephemeral channels show evidence of fluvial processes but have flows only during and shortly after precipitation events (Halwas et al. 2005).

During extended periods of low flow, the water table may drop below the streambed because of a combination of reduced runoff generation from upslope areas and transpiration by riparian vegetation. Under these conditions, sections of streams dry up wherever stream discharge is insufficient to maintain continuous surface flow and to satisfy water losses through the streambed and banks. Stream drying may occur frequently in the upper portions of the channel network, which can interrupt connectivity (Hunter et al. 2005). For example, Story et al. (2003) found that dewatering of an intermediate segment of stream channel effectively decoupled a lower reach from the warming effects of harvesting and road construction on an upper reach of a small stream in the central interior of British Columbia.

The use of various terms to define streams can cause confusion. For example, "headwaters" is sometimes used to refer to the sources of any stream, regardless of its size (Gomi et al. 2002; Moore and Richardson 2003). In this chapter, headwater streams are defined as having no perennially flowing tributaries (Gomi et al. 2002; Moore and Richardson 2003; Richardson and Danehy 2007). This narrow definition distinguishes headwaters from networks of streams (Gomi et al. 2002), placing the focus instead on the different processes governing headwaters versus non-headwaters and on the different management strategies available for these two channel types (see Gomi et al. 2002; Richardson and Danehy 2007).

Influence of Channel Type on Habitat

Channel components such as pools, riffles, steps, cascades, and plane beds provide important habitat for many organisms (Chapter 10, "Channel Geomorphology: Fluvial Forms, Processes, and Forest Management Effects"). Variations in the hydraulic characteristics of different reaches and channel sub-units create distinctive habitat characteristics that influence the spatial distributions of aquatic organisms (Hawkins et al. 1993). For example, riffles, a common channel feature, are characterized by relatively high flow velocities. This channel feature is favoured habitat for a diversity of aquatic organisms that filter fine particles of organic matter or prey from the water column and that require sufficient flow to bring these materials to them. Larval blackflies and net-spinning caddisflies, for example, can filter large masses of particles from passing water (Wallace and Merritt 1980), removing this load of organic material from water supplies and thus providing an important ecosystem service. Fish often require particular channel features during different life cycle stages. Adult salmonids (Pacific salmon, trout, char) generally use riffles for spawning redds, whereas juvenile salmonids usually inhabit pools. Within these pools, young salmon take advantage of cover behind boulders or logs, finding refuge from the full hydraulic force of the channel flow but still having ready access to prey carried along in the current (i.e., "drift").

Hydrology

Hyporheic exchange flow refers to the transfer of stream water through the streambed and banks (recharge), the down-valley transport of this water within the saturated zone surrounding the stream channel, and the subsequent discharge from the subsurface back into the channel (Figure 13.1). Hyporheic exchange flow occurs in response to variations in hydraulic potential along the streambed and banks and takes place at a range of spatial and temporal scales. For example, at a small scale, water pressure is often higher on the upstream side of bedforms than on the downstream side; the resulting hydraulic gradient induces infiltration of stream water on the upstream side of the bedform and discharge on the downstream side. This type of exchange flow is important for salmon redds, where the through-flow of surface water maintains high dissolved oxygen. This topic is covered in more detail in Chapter 14 ("Salmonids and the Hydrologic and Geomorphic Features of Their Spawning Streams in British Columbia").

Hyporheic exchange flow is controlled primarily by the morphology of the valley floor and stream channel (Harvey and Bencala 1993; Wroblicky et al. 1998; Kasahara and Wondzell 2003; Gooseff et al. 2006; Wondzell 2006). In steep headwater streams, hyporheic exchange flow can be controlled by boulder or log steps in the longitudinal profile of the stream (Kasahara and Wondzell 2003; Anderson et al. 2005). The volume of sediment stored above these steps largely determines the extent of the hyporheic zone. Downwelling stream water seeps into the

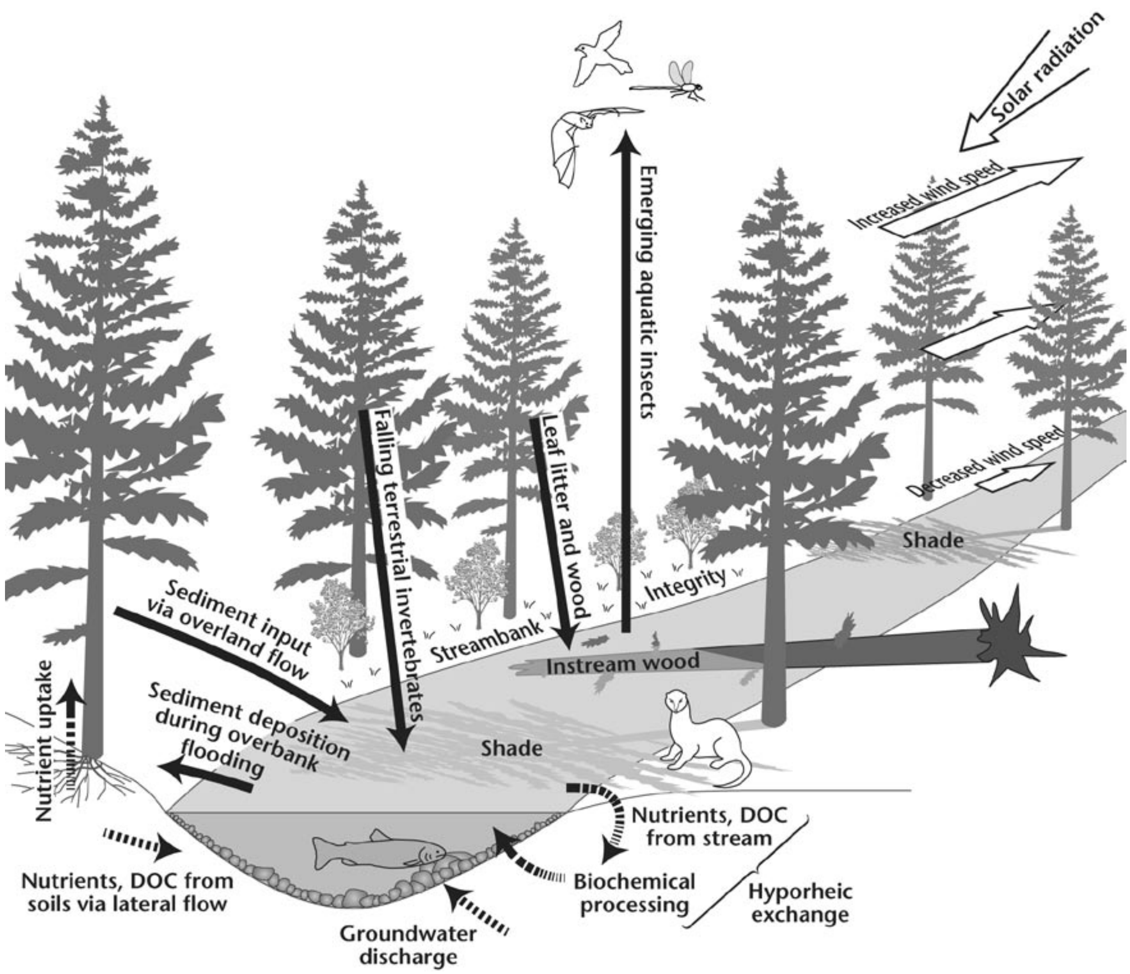

FIGURE 13.1 *A stream reach showing many of the elements and processes that link streams and riparian areas (E. Leinberger, University of British Columbia).*

streambed upstream of the steps and returns to the stream channel below the steps, where it upwells through the streambed (Harvey and Bencala 1993; Moore et al. 2005b; Scordo and Moore 2009).

In streams with riffle-pool morphology, channel water tends to flow into the streambed and banks at the riffle heads and discharge back into the stream in the downstream pools (Harvey and Bencala 1993; Kasahara and Wondzell 2003; Anderson et al. 2005). In larger, unconstrained streams with relatively wide and flat floodplains, exchange flows occur through mid-channel bars. Stream water flows into the bars through the streambed and bank on the upstream side, and returns to the stream channel on the downstream side (Vervier and Naiman 1992; Kasahara and Wondzell 2003). Exchange flows across gravel bars also support upwelling of stream water into floodplain springbrooks where abandoned channels are incised below the water table (Wondzell and Swanson 1996, 1999). Where streams meander through a floodplain, hyporheic flow paths typically shortcut the meander bends; water infiltrates across the downstream bank of one bend and re-emerges at the upstream bank of the following meander segment.

In wide, gravel-filled glaciated valleys, the bedrock underlying the alluvium often has sills that rise toward the alluvial surface alternating with over-deepened basins. In these situations, water typically leaves the stream near the head of a basin, flows down-valley near the base of the alluvium, and then is forced to emerge at the downstream end of the basin by the confining effect of the bedrock sill (Malard et al. 2002).

Water Chemistry and Temperature

Sources of hyporheic water include shallow subsurface flow from hillslopes, upwelling of deeper groundwater, and infiltration of channel water through the streambed and banks. Consequently, hyporheic zone water chemistry varies in both time and space due to variations in chemistry of the different water sources, and the associated rates of supply, flow paths, and mixing within the hyporheic zone. Because of the contributions of channel and hillslope water, hyporheic zones are biogeochemically distinct from groundwater. For example, the hyporheic zone tends to have enhanced dissolved oxygen, particularly near the recharge zones where oxygenated channel water infiltrates the streambed and banks (Ward et al. 1998). The contrasts in biogeochemistry between groundwater and the hyporheic zone are particularly important in relation to nitrogen processing. Information on nitrogen cycling in terrestrial and aquatic ecosystems is provided in Chapter 12 ("Water Quality and Forest Management").

The hyporheic zone is often thermally intermediate between surface water and groundwater. The water temperature in shallow sediments in hyporheic recharge zones usually follows diurnal and seasonal fluctuations in stream temperature but with a lag and attenuation that increases with depth (Moore et al. 2005b; Arrigoni et al. 2008).

Biology

Biologically, hyporheic zones provide habitat for a set of aquatic species that includes some not found in surface waters, and most of which are microscopic. Some of these taxa are rarely seen other than by people who expressly look for them; consequently, very little work has been done in British Columbia on these species. These taxa include a variety of rotifers, copepods and other crustaceans, nematodes, and gastrotrichs (Ward et al. 1998). Increasing evidence shows that some macro-invertebrate species (e.g., Capniidae stoneflies) live much of their life in the hyporheic zone and come to the bed surface only when nearing completion of the larval stages before emergence as a flying adult. These organisms feed on biofilm, the thin microbial layer growing on wet surfaces supported by dissolved organic carbon (DOC), and on particulate organic matter in the interstitial spaces in the hyporheic zone. These tiny invertebrates can move easily through the small interstitial spaces and may find refuge from predators and the forces associated with flowing waters.

Definition

The riparian zone has been defined in various ways, and the definition applied depends on the context in which it is used. The riparian zone has been referred to as the ecotone between aquatic and terrestrial realms (Naiman and Décamps 1997). The zone is often defined based on diagnostic plant communities; however, the applicability of this approach differs according to climatic context. In xeric (or seasonally xeric) landscapes, a strong gradient often exists from the vegetation associated with riparian areas to that of upslope areas. In mesic landscapes, such as those found in coastal areas, the contrast between upslope forest and riparian zones may be subtle or non-existent (Hibbs and Bower 2001).

From a functional perspective, the riparian zone is considered to be the portion of the terrestrial environment that exerts influence on a stream and (or) that is influenced by the water body (Gregory et al. 1991; Richardson et al. 2005b, Figure 13.1). The influences of streams on riparian areas are frequently expressed through differences in microclimate (e.g., Moore et al. 2005a; Rambo and North 2009). In addition, riparian soils often differ owing to periodic inundation by groundwater or overbank flows, which directly influence soil-forming processes and can lead to the development of Gleysols.

Management guidelines commonly define the riparian zone in terms of the width of a riparian buffer (Gregory et al. 1991; Forest Ecosystem Management Assessment Team 1993; Richardson et al. 2005b). The management guideline is the most arbitrary definition, but it is also the most pragmatic because it captures many of the functions of riparian–stream interactions and is simple to measure. A comprehensive review of the methods used to define and delineate riparian management areas (or zones) is provided in Forest Ecosystem Management Assessment Team (1993) and Chapter 15 ("Riparian Management and Effects on Function").

Riparian areas associated with lakes, wetlands, estuaries, and the ocean have special characteristics. Soils at the edges of these water bodies may remain saturated for most of the year if the surrounding area has little elevational gradient compared to areas with steeper gradients. This contrast in soil moisture condition can be an important determinant of riparian plant communities. Vegetation communities at the edge of lakes, wetlands, estuaries, and the ocean may show evidence of greater specialization than communities that border flowing waters; for instance, these communities may include extensive areas of rushes (e.g., *Juncus* spp.) and cattails (e.g., *Typha* spp.) that grade into partially submerged species (e.g., *Potamogeton* spp., *Nuphar*).

Functions of Riparian Vegetation

Riparian vegetation strongly influences both stream and riparian zone processes (Gregory et al. 1991). The magnitude or degree of coupling of instream processes with riparian vegetation partly depends on stream size (Richardson and Danehy 2007). For example, the forest canopy can cover the entire width of a small stream, shading the streambed from most light input. A larger stream, by creating a wider gap in the vegetation, may be exposed to direct sunlight over part of its area. This in turn affects the microclimate, thermal regime, and primary productivity of the stream (Figure 13.1).

Forest canopies can intercept 95% or more of the light reaching the canopy. The amount of light actually reaching the level of the stream depends on latitude, time of year, time of day, cloud cover and type, stream width, overstorey canopy characteristics, and shading by the streambanks and surrounding topography (Figure 13.2). The effect of the canopy on light infiltration can vary seasonally where deciduous trees are an important component of the riparian community (Hill et al. 2001). It can also vary over decadal and longer time scales in association with the state of forest development (second-growth forests typically intercept more light than old forests) and disturbance history (e.g., fires, blowdown). Increased light levels reaching the stream surface after disturbance can result in enhanced rates of primary production (Kiffney et al. 2003; Melody and Richardson 2007), depending on whether nutrients or other factors are limiting. Photosynthetically active radiation (PAR) and ultraviolet (UV) radiation can be intercepted by canopy vegetation, and can increase after the canopy has been opened by forest harvesting, fire, or insect damage. Light inputs (including UV, especially UVB, radiation) can negatively affect many organisms (Kelly et al. 2003). Ultraviolet

FIGURE 13.2 *Small stream at the University of British Columbia's Malcolm Knapp Research Forest (Stream G); note that with a 10-m riparian reserve on each side the stream channel is still mostly shaded from incoming solar radiation by canopy and shrub-layer vegetation. (Photo: J. Richardson)*

inputs can be attenuated by water depth or by high concentrations of DOC, which tends to increase following forest harvesting.

Riparian forests contribute to bank stability (Eaton et al. 2004) and strongly influence the rate and kind of organic matter inputs. The influence of vegetation also varies with the sizes of plants. In general, a closed tree canopy shades a stream more effectively than the herb or shrub layer, although small streams can be shaded effectively by understorey vegetation (e.g., Macdonald et al. 2003; Teti 2006).

Riparian vegetation influences microclimate by affecting solar radiation, longwave radiation, air temperature, humidity, and wind speed. Relative to an open site, forest cover tends to decrease solar radiation, increase incident longwave radiation, decrease wind speed, and moderate diurnal air temperature variations (Moore et al. 2005a). Decreased wind speed limits ventilation above and near streams; consequently, riparian zones are usually more humid than upslope areas (e.g., Danehy and Kirpes 2000) because the stream is a source of moisture.

Hydrology of the Riparian Zone

Hydrologically, the riparian zone functions to transmit groundwater and hillslope water to the stream channel. In addition, when the riparian water table rises to the ground surface, infiltration of rainfall and snowmelt is impeded, producing saturation overland flow (Hewlett and Hibbert 1967; Troendle 1985; Burns et al. 2001; McDonnell 2003; Buttle et al. 2004). Two-way exchanges of water between the stream and the riparian aquifer (i.e., hyporheic exchange) can also occur.

Transpiration by riparian vegetation can extract water from the riparian zone, drawing down the riparian water table and producing a diurnal decrease in streamflow followed by recovery at night (Dunford and Fletcher 1947; Hewlett 1982; Bond et al. 2002). However, the timing and magnitude of these streamflow fluctuations vary with discharge, likely caused by changes in travel time and the downstream routing of streamflow fluctuations from different parts of the catchment (Wondzell et al. 2007). The magnitude of this process is also strongly affected by temperature, soil moisture regime, and vegetation types.

Water Quality

Forested riparian areas are often characterized as filters, intercepting sediments and nutrients that would otherwise enter streams (Lowrance et al. 1997). Removal of nutrients, such as nitrogen, is accomplished by plant uptake of riparian groundwater as it flows from surrounding slopes toward the stream (Castelle et al. 1994). The riparian zone can also trap sediments because its lower gradient reduces the transport capacity of overland flows. In addition, riparian vegetation provides flow resistance.

These observed water-quality functions have been well demonstrated in agricultural settings, and have led to recommendations for retaining forested reserves along streams. However, these water quality functions have been less well studied in forested catchments, and may be less important than in agricultural catchments. For example, several studies in the Pacific Northwest and elsewhere have shown that infiltration excess overland flow in areas with severely disturbed soils and saturation excess overland flow in topographic convergence zones may transport significant amounts of sediment from hillslopes to a stream even though the stream has an intact riparian buffer (Belt and O'Laughlin 1994; Rivenbark and Jackson 2004; Gomi et al. 2005).

Wood

Wood, large and small, performs several functions in stream and riparian systems. It can function as a geomorphic structure, as a place for interception and storage of organic matter, as cover for organisms, as a substrate, and even as a source of nutrition (e.g., Richardson 2008). Large wood is well known for contributing to stream channel stability. This function is discussed in detail in Chapter 10 ("Channel Geomorphology: Fluvial Forms, Processes, and Forest Management Effects"). Large wood contributes to the diversification of channel sub-units, and is especially important in the formation of plunge and scour pools, which provide habitat for many instream species.

Wood provides important habitat elements for organisms in streams (and riparian areas). Single logs, debris jams, and other accumulations of wood provide security cover for organisms seeking refuge from predators. Small fish can hide from predators among wood accumulations (Roni and Quinn 2001; Boss and Richardson 2002). The signal crayfish (*Pacifastacus leniusculus*), the sole species of native, freshwater crayfish in British Columbia, is most often found in wood accumulations where it hides from predators, such as river otters and mink (Bondar et al. 2005). Wood provides shelter from the full force of the stream current. This can allow fish and other organisms to occupy the water column without having to struggle against strong flows. In addition, wood contributes to the storage of fine sediments by damming and locally reducing the bed slope. The stored fine sediments may provide important spawning substrate for some species.

Organic matter would be easily entrained from the streambed and washed downstream if it were not for the presence of instream wood. A large proportion of organic matter gets stored temporarily against wood. Small pieces of wood, a single large piece, or a debris jam can all trap organic matter. The retention of organic matter over an extended period allows it to be broken down and utilized by the local aquatic community.

Wood provides a substrate for attachment for some organisms. This has not been demonstrated in British Columbia or the Pacific Northwest but, in other parts of the world, a number of aquatic organisms use wood preferentially as an attachment site. This is especially true for "collectors"—organisms that filter fine particles of organic matter that passes by in the water column (e.g., Benke et al. 1984).

Finally, wood provides a source of food, particularly for biofilm (see further detail below), which can use the wood as a carbon source or extract dissolved carbon from the passing water. Examination of well-decayed wood in many streams in British Columbia frequently reveals the presence of many small organisms, especially stonefly larvae (Nemouridae) and midge larvae (Chironomidae). The role of wood as a substrate versus a food source is not easily distinguished for many organisms. For example, numerous invertebrate species consume biofilm from the wood surface, and it may constitute the largest proportion of some species' diets (Bondar et al. 2005; Eggert and Wallace 2007). The stomachs of adult signal crayfish were shown to contain large amounts of wood, and a stable isotope signature of the crayfish body matches biofilms growing on wood (Bondar et al. 2005). Some species feed almost exclusively on wood (referred to as xylophagy), including larvae of the elmid beetle (*Lara avara*) and larvae of a cranefly genus (*Lipsothrix* spp.; Dudley and Anderson 1982). An estimate of the quantitative contribution of wood to stream food webs has still not been attempted.

Bank Stability and Windthrow

Vegetation growing along the riparian area helps stabilize the stream channel in several ways. Plant roots bind to mineral substrate, making the streambank better able to resist the erosive forces of moving water (e.g., Eaton et al. 2004; Sakals and Sidle 2004). If riparian vegetation is of sufficient size (e.g., large trees), it can also trap wood that is transported during floods, and thereby contribute to bank stability, the formation of gravel bars, and the initiation of debris jams (Swanson et al. 1998). Windthrow can either stabilize or destabilize channels, depending on how it interacts with fluvial sediment transport processes. Windthrown streamside trees can increase sediment inputs to the channel via the root wad (Grizzel and Wolff 1998).

ORGANIC MATTER DYNAMICS IN STREAM-RIPARIAN SYSTEMS

Autochthonous Inputs

Primary production (photosynthesis) is the source of most biologically fixed energy available to food webs. We distinguish between *in situ* production (autochthonous) and production derived outside the local system (allochthonous). In riparian areas, many kinds of plants contribute to productivity. Likewise, within streams, primary producers such as algae can contribute to the energetic basis of stream food webs. In general, plant productivity is limited by nutrients (e.g., nitrogen, phosphorus, and potassium) or light, or some combination of these two factors (Kiffney et al. 2003, 2004). In streams with relatively open canopies (i.e., high light environments), primary production can be the dominant contributor to instream production (Minshall 1978). Some types of primary producers in streams are described below (see "The Biota of Streams and Their Riparian Areas" below).

Allochthonous Inputs to Streams

Various types of organic matter from the riparian and upslope areas can enter a stream (i.e., they are allochthonous; Figure 13.1). These materials occur as particulate (e.g., leaf litter, terrestrial invertebrates) or dissolved forms of matter (e.g., via groundwater discharge). In most streams, organic matter in the form of leaf litter and wood provides the main form of energy for stream food webs (Richardson et al. 2005a). The rate, timing, particle size, and quality of organic inputs vary with stream size, time of year, and forest type. Small streams have the highest inputs of leaf litter per unit surface area; as stream size increases, advection of particulate matter from upstream becomes the dominant source of fluvial organic matter within a stream reach.

Dissolved organic matter (DOM), or dissolved organic carbon (DOC), reaches the stream via groundwater discharge. DOC is colloidal and not truly dissolved, and is operationally defined as organic matter that can pass through 0.63-µm filter paper (Richardson et al. 2005a). Quantitatively, DOC may be the single largest flux of organic matter through streams (Kiffney et al. 2000); however, it is not easily stored because it gets flushed through the channel. It is used as an energy source primarily by bacteria, but it may also flocculate (weakly aggregate into larger particles) and can then be captured and consumed by organisms such as blackfly larvae (Ciborowski et al. 1997). Dissolved organic carbon often makes water tea-coloured, enhancing interception of UVB radiation that would otherwise damage stream organisms (Kelly et al. 2003). The specific qualities of DOC vary widely, and its value as a resource depends partly on its source (McArthur and Richardson 2002).

Particulate organic matter includes mainly leaf litter, seeds, small branches, and bark, all of which can contribute to the energy base of streams (Richardson 1992). It is generally classified as coarse particulate organic matter (CPOM; > 1 mm^2) or fine particulate organic matter (FPOM; < 1 mm^2 and larger than dissolved). The distinction by particle size relates to the two primary groups of decomposers: fungi decompose CPOM and bacteria decompose FPOM. The size fractions also match the modes of foraging by consumers: CPOM is eaten by animals (mostly invertebrates) known as "shredders" and FPOM is eaten by "collectors."

The largest proportion of the organic matter load enters the stream in autumn and is used up by the following spring, which may result in periods of food limitation (Richardson 1991). In British Columbia, organic matter enters stream channels year-round. In particular, red alder, a common riparian tree in coastal British Columbia, can drop large numbers of leaves starting as early as June in most years, with peak leaf drop occurring in October and November.

Cross-ecosystem Subsidies

Stream ecosystems receive large inputs of organic matter from the riparian zone, especially leaf litter from riparian vegetation, but also by inputs of seeds, fruits, and terrestrial invertebrates that often drop from the riparian zone to the stream surface. These inputs represent a "cross-ecosystem resource subsidy," whereby organic matter production in one ecosystem is consumed by (and subsidizes) another (Polis et al. [editors] 2004; Marczak et al. 2007b; Richardson et al. 2009). The significance of these subsidies is increasingly recognized. Another example of a resource subsidy is the input of terrestrial invertebrates falling from the riparian canopy into streams. For example, some salmonids, such as coho and cutthroat trout, may gain more than 50% of their food energy from terrestrial invertebrates (Wipfli 1997). Other species, such as water striders, also depend on inputs of terrestrial invertebrates; consequently, aquatic organisms may have to compete for fast access to these inputs (Marczak et al. 2007a).

Cross-ecosystem subsidies can also transfer energy from the stream to the riparian zone. For example, adult aquatic insects are used as food sources by some riparian species, such as birds, bats, and dragonflies. Subsidies also operate along the stream network; for example, invertebrates are transported downstream from fishless headwater streams to larger, fish-bearing reaches. In addition, terrestrial vertebrates such as bears and mink depend on fish as a significant food source, although these latter sources of food may not strictly be subsidies (see Richardson et al. 2009 for further details).

Small streams can have relatively high rates of productivity and some of that production is moved downstream to larger streams where consumers, such as salmonid fish, may be able to capitalize on these resources (Wipfli and Gregovich 2002). Subsidies of resources and materials from headwaters to downstream ecosystems can be substantial (Wipfli et al. 2007). The magnitudes of these fluxes make it apparent that small streams are important contributors to fish production downstream. Within large rivers, the processing of materials to finer particles can provide an enormous flux of particles to downstream reaches (Malmqvist et al. 2001).

THE BIOTA OF STREAMS AND THEIR RIPARIAN AREAS

Terrestrial Species

Streams and riparian areas provide critical habitat for many terrestrial animals, plants, and other organisms during some stage of their life cycles. These organisms are referred to as "riparian obligates" and include stream-breeding amphibians and some species of waterbirds and mammals. "Riparian associates" are species that are more abundant in riparian than in upland areas, but do not depend solely on riparian areas to complete their life cycle (Richardson et al. 2005b; Mallik and Richardson 2009).

Amphibians are typically riparian obligates (some Plethodontidae salamanders in British Columbia are not) because they depend on water for their larval stages or other life history stages. In British Columbia, three species of amphibians are obligate stream-breeders: (1) the coastal tailed frog (*Ascaphus truei*), (2) the Rocky Mountain tailed frog (*A. montanus*), and (3) the coastal giant salamander (*Dicamptodon tenebrosus*). These species lay eggs in cobble-bottomed streams and the larvae are restricted to streams until metamorphosis (which may take as long as 4 years). In these three species, larval growth is affected by stream productivity and temperature (Kiffney and Richardson 2001; Mallory and Richardson 2005; Matsuda and Richardson 2005). Populations of these stream-associated amphibians are negatively affected when fine sediments are introduced into the aquatic environment—growth rates are reduced, interstitial habitats are in-filled, and their capacity to hold on to the rocky substrate is potentially impaired (Welsh and Ollivier 1998). Toads and other amphibians are also sensitive to changes in freshwater habitats, such as increases in sedimentation, changes in algal resources, and increases in water temperatures (e.g., Wood and Richardson 2009).

Other vertebrate riparian obligates use riparian zones for foraging and (or) nesting. Riparian obligates typically rely on streams as a source of food. For example, dippers, harlequin ducks, spotted sandpipers, and water shrews feed largely on stream invertebrates, whereas river otters, kingfishers, and mergansers prey heavily on fish. The beaver is another riparian-obligate species that depends on deep-water habitats, usually created by dams, for refuge from predators and as a place to store winter food supplies. In turn, beavers modify stream channels in ways that provide important habitat elements for other species (e.g., Stevens et al. 2007). A large percentage of British Columbia's vertebrates are considered riparian obligates, and over half of all terrestrial vertebrate species in the province are considered at least riparian associates.

Many species of invertebrates, bryophytes, vascular plants, and fungi are also associated with riparian zones; however, our lack of basic knowledge about many species within these groups makes it difficult to determine the nature of their dependence on riparian areas. In one set of studies conducted in Sweden, bryophytes and snails were shown to be strongly associated with the riparian areas of small streams, and were seriously affected by forest harvesting even when 10-m reserves were provided (Hylander et al. 2004). Some spiders may be specially adapted to capture the emergent adults of aquatic insects (e.g., Marczak and Richardson 2007). Other organisms, such as dragonfly adults, also take advantage of this food source.

Vascular Plants, Mosses, Algae, and Microbes

A diverse assemblage of organisms including all the kingdoms of life, many of which are microscopic, inhabit streams. A number of vascular plants, also referred to as macrophytes, are found in moving water, although usually slow-moving water. These include pondweeds of the genus *Potamogeton*, as well as sedges, rushes, and cattails found along marginal areas. In general, rooted plants are relatively uncommon in British Columbia's streams. Mosses can be prevalent on stable rock surfaces in streams.

The complex mixture of small organisms generally referred to as biofilms are attached to most surfaces in streams. The organisms within this mixture include algae, bacteria, and fungi, as well as small organisms (protists and small animals) that feed on the biofilms. Biofilms develop very rapidly, have very high productivity, and may be a predominant source of food for consumers in some streams (Allan and Castillo 2007). The term "periphyton" is sometimes used, although this refers strictly to the algae component, and algae are usually associated with other organisms of the biofilms, so biofilm is the correct term for most applications.

Algae are single-celled, primary producers; that is, they are photosynthetic and grow on any surface (rocks, wood, plants, invertebrates) where they get energy from light and nutrients (e.g., nitrogen and phosphorus) from water. Algae are a taxonomically diverse grouping and represent many different phyla (divisions) within the plant and protist kingdoms. These groups include diatoms, green algae, red algae, and golden algae (Figure 13.3). Blue-green algae (Cyanobacteria) are a phylum of photosynthetic, nitrogen-fixing bacteria that are not constrained by the amount of fixed nitrogen in water. Most algae are small cells attached in some way to mineral and organic surfaces, where they form a thin, slippery mat tens of micrometres thick. Some species of algae form long filaments of cells, often protected by a mucilaginous sheath, which makes it difficult for small animals to eat them and allows the species to grow in the short term without control other than limitations of nutrients and space. Cyanobacteria can also avoid consumption by producing toxins as well as physical defences. One species of diatom (*Didymosphenia geminata*) forms thick mats that cause various problems in streams around the world, including within British Columbia. For more information on stream algae see Stevenson et al. (1996).

Bacteria are ubiquitous in streams, and generally obtain energy from DOC and nutrients from the passing water (or DOC excreted by algae within the biofilms). Bacteria are found on any surface, and some are thought to extract energy from both FPOM and DOC. Particles of FPOM that are fecal aggregates from stream invertebrates provide a large surface area for bacterial growth. Most bacteria are not generally harmful to humans, but certain types are toxic, and agencies monitor specifically for groups

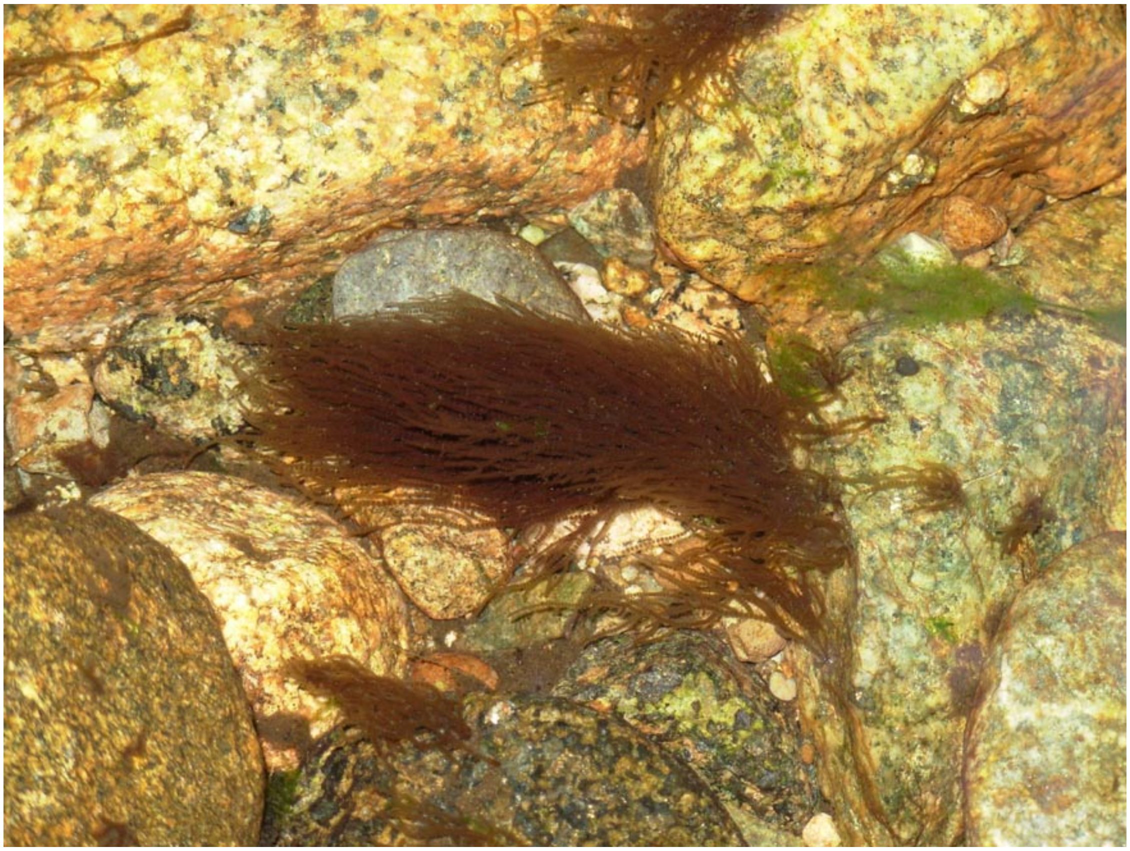

FIGURE 13.3 *Examples of two types of macroscopic stream algae, one a red algae (Rhodophyta) and the other a green algae (Chlorophyta) (top right of photo). The large clump of red algae in the middle is about 10 cm long. Most algae are microscopic. (Photo: J. Richardson)*

considered dangerous, such as *E. coli* and coliform-shaped bacteria.

Fungi in streams, referred to as "aquatic hyphomycetes," include hundreds of described species, but their taxonomic status and relation to terrestrial fungi is unclear. Fungi use CPOM (wood, leaves) as a carbon source and obtain nutrients from the water. Fungal spores colonize CPOM, establishing a mycelium (similar to a root system) that requires particles greater than about 1 mm in diameter. Because these fungi require a large particle of organic matter, they are found only in biofilms growing on organic surfaces. Fungi are considered to dominate the process of decomposition of leaves, wood, and animal carcasses in streams, and serve as an intermediate trophic level making cellulose (and other complex carbohydrates) available to consumer animals.

Stream Invertebrates

Freshwater invertebrates are described in numerous ways, either taxonomically or by functional attributes. Invertebrates are often called "benthos" (or described using the adjective "benthic"), which refers to their association with the bottom of a water body such as the streambed. Invertebrates occupy all major ecological roles one could expect in streams. They are consumers of basal resources (algae, biofilms, organic matter), and secondary consumers. They are the link from basal resources to higher trophic levels, including fish. One common way of describing freshwater invertebrates is by functional feeding group, or FFG (Cummins 1973; Merritt et al. 2008), a categorization based on what the species feeds on and how it gets its food. The primary FFGs, known as the "predators," include groups that engulf food as well as those that pierce and suck their prey. Another group, known as the "shredders," includes detritivorous invertebrates that feed on coarse particulate organic matter. Species that gather fine particulate organic matter are referred to as "collectors"; these organisms may use a filter of some sort ("filterers"; e.g., a modified body part or a net made of silk or mucous) or gather food using mouth brushes or other modifications ("gatherers"). Organisms that eat biofilms or algae from rock or wood surfaces are known as "scrapers" or "grazers." A special kind of grazer is a group of organisms known as "xylophages" that scrape wood surfaces. The last of the invertebrate feeding groups are parasitic, and include species from the Nematoda (wire worms) and the Nematomorpha (horsehair worms).

Few accurate estimates exist of the numbers of invertebrate species in British Columbia. Cannings (2002) estimated that 87 species of dragonflies and damselflies (order Odonata) occur in the province. Of these dragonflies, 20 are either red- or blue-listed species. Molluscs, including freshwater mussels, snails, limpets, are another taxonomic group of invertebrates that includes many at-risk species in British Columbia, with 21 species either red- or blue-listed. Other orders of freshwater invertebrates in British Columbia are much less known, but species number easily in the thousands.

One particular use of freshwater invertebrates is as indicators of water quality and environmental condition. The community structure (composition and relative abundances) of invertebrates reflects the physical, chemical, and biological condition of a site by integrating all local and catchment-scale influences. Two primary sets of indicator tools have been developed: the "Reference Condition Approach" and "Benthic Index of Biotic Integrity." These approaches compare the community structure of a set of reference sites (assumed to be without environmental impacts) to a test site in order to determine whether the community structure diverges from what is predicted (e.g., Bailey et al. 2004; and see Chapter 17, "Watershed Measurement Methods and Data Limitations").

Fish

Many species of fish, particularly salmonids, are associated with streams. British Columbia has 75–80 species of freshwater fish (McPhail 2007). Most of these species are resident (i.e., non-anadromous), spending their entire life cycle in freshwater, although not necessarily always in streams. Some species move to different freshwater habitats depending on their life stage and the time of year (e.g., white sucker, Chinook salmon, bull trout, grayling).

Adults of anadromous species, such as salmonids and smelts (e.g., oolichan), return from the marine realm to freshwaters in large numbers. This return is an important part of stream ecology, form, and function (e.g., Hassan et al. 2008; Chapter 14, "Salmonids and the Hydrologic and Geomorphic Features of Their Spawning Streams in British Columbia"). Salmon provide direct and indirect inputs to aquatic environments by providing nutrients and an easily consumed resource complete with protein and fatty acids in the form of the carcass or salmon eggs (e.g., Zhang et al. 2003); however, toxins that bioaccumulate in the bodies of fish when they are in the marine environment can also be carried into terrestrial food webs (Christensen et al. 2005). For additional information on fish of British Columbia, see Groot and Margolis (editors, 1991), Richardson et al. (2000), and McPhail (2007).

ECOLOGICAL FUNCTIONS OF STREAMS IN WATERSHEDS

Longitudinal and Lateral Linkages

Streams are the receiving environment for materials transported by processes within catchments (watersheds) and are intimately linked to the surrounding basin. As described earlier in this chapter, these linkages take many forms. For example, groundwater entering streams carries with it signatures of the organic material in the forest floor and chemistry of the soils and bed materials it flows through. The concentration of DOC carried by groundwater varies through time (Kiffney et al. 2000) but little is known about the qualitative differences in organic components (McArthur and Richardson 2002). Leaf litter and other organic materials enter streams directly from the riparian forest canopy, although these materials are also carried in laterally from adjacent areas (referred to as "lateral transport"). Lateral delivery mechanisms include wind, advection from ephemeral channels, or even saturation overland flow.

An important distinction between the headwater and downstream portions of a stream network is the degree of coupling between the stream and the hillslopes. In headwater streams, this coupling is strong, so that disturbances occurring on the slopes (e.g., an increase in soil erosion) can directly influence stream processes. In downstream reaches where the stream may flow within a low-gradient floodplain, the coupling is weaker, and stream processes are more sensitive to disturbances in the riparian zone, or to disturbances in the headwaters that propagate downstream. For these reasons, it is appropriate to adopt different management strategies in different portions of the stream network.

Materials delivered to streams from upslope source areas or the riparian zone can be transported downstream (Chapter 10, "Channel Geomorphology: Fluvial Forms, Processes, and Forest Management Effects"). Small streams, especially most headwaters, are relatively incompetent to carry large materials, and therefore tend to accumulate large clasts and wood that remain in place for long periods of time (i.e., colluvial material). This material only moves downstream to larger channels during infrequent, large debris flows (Chapter 8, "Hillslope Processes"). In environments where debris flows do not occur (e.g., low-gradient headwaters in the Interior Plateau), rates of downstream transport of mineral sediment and wood are constrained by the rates at which this material weathers or decays in situ to size classes that the stream is competent to move.

Channelized debris flows occur as brief, punctuated episodes, but as a consequence of moving large amounts of rock and wood stream channels are reshaped along with the habitat they provide (e.g., Swanson et al. 1998). The resulting changes in morphology can be long lasting. Some elements of the stream system recover relatively quickly (e.g., Lamberti et al. 1991) but others may take decades to stabilize.

Over longer time scales, stream erosion shapes the morphology of the riparian zone (e.g., by bank erosion and channel migration) and also interacts with hillslope processes (e.g., by undercutting footslopes). In these ways, stream erosion can modify the nature of coupling between the stream, its riparian zone, and the catchment as a whole.

The organization of the stream network and its lateral interactions varies with physiographic setting. For example, mountainous catchments typically have high gradients in the headwaters, with a dominant trend to lower gradients and decreased coupling in the downstream direction. In contrast, streams draining the interior plateaus may have relatively low-gradient reaches in their headwaters, often including wetlands, ponds, and small lakes, located upstream of reaches with high gradient and strong coupling where the streams are actively cutting through the plateau bedrock toward the level of a larger stream occupying a major valley (e.g., streams draining the Bonaparte and Nehalliston Plateaus located west of the North Thompson River).

Conceptual Models of Stream Ecosystem Organization

Three primary conceptual models highlight the spatial and temporal scaling of ecological processes within streams: (1) the River Continuum Concept (Vannote et al. 1980), (2) the Riverine Productivity Model (Thorp and Delong 1994), and (3) the Flood Pulse Model (Junk 1999). The River Continuum Concept (RCC) describes the linear variations in stream ecology from a stream's source to its mouth based on changes in characteristics such as stream size, gradient, biological energy sources, and temperature regime. As described above, the intensity of the linkages between a stream and its surroundings scales with stream size, particularly in relation to width; however, channel gradient and maximum flows also vary with stream size, producing longitudinal variations in stream power and tractive force. Although the RCC captures several important scale linkages governing stream ecology, it does not account for the branching network structure of a channel network and the important ecological role of tributaries (Gomi et al. 2002; Grant 2007). In addition, the RCC provides a static description of stream ecology, and does not explicitly recognize that streams evolve through time and interact with their landscape (Ward 1989). Some of the physical features observed in a stream can reflect the antecedent conditions caused by past channel-modifying flows or sediment inputs rather than the current flow regime and sediment supply.

The stream network concept is particularly important in relation to population dynamics and species diversity, especially in headward streams that can vary in their disturbance histories across a landscape. Streams high in the network may experience relatively higher rates of local extinction because of the limited population sizes they can support, as well as relatively lower rates of recolonization because of the distance from nearest sources (Fagan 2002). These extinction-recolonization dynamics may be one reason for the occurrence of relatively fewer species, especially large-bodied species, as one goes up a drainage network. The network perspective provides important insights for the conceptualization and management of watersheds that are only just starting to permeate management agencies (Richardson and Thompson 2009).

The Riverine Productivity Model (RPM) emphasizes the lack of a continuous, longitudinal gradient in streams, and points to the nesting of hydrogeomorphic patches in streams (Thorp and Delong 1994). This view integrates variation in channels as an array of geomorphic elements at many spatial and temporal scales, more in line with a geomorphic perspective. It also highlights the local influence of hydrogeomorphology on species occurrences and biological processes. The RPM, as with the Flood Pulse Concept, better integrate lateral connectivity with floodplains than does the RCC (Junk 1999). The Flood Pulse Concept emphasizes the links across the stream-floodplain margin that result in movements of nutrients, sediments, wood, and species across the boundaries, and it varies temporally, especially during floods (Junk 1999; Richardson et al. 2009). This latter concept suggests that stream processes cannot be understood without consideration of the connections with the surrounding floodplain, riparian areas.

Spatial and Temporal Dynamics: Disturbance Regimes, Nutrient Spiralling, and Serial Discontinuity

Periodic disturbances can rearrange structures and functions of aquatic ecosystems, and allow the organizing processes to re-exert themselves. Disturbance is defined in many ways. One simple approach considers disturbances as events where some process exceeds the long-term mean plus two standard deviations (see Resh et al. 1988). In streams, disturbances include floods, low flows, channelized debris flows, fire, and other events that dramatically alter the streamscape. For example, extreme flows can mobilize large structural elements of streams and rearrange large wood and boulders, disrupting the physical habitat and food supplies within the channel and beyond.

Streamflow in channels moves materials, including organic particles and dissolved nutrients as well as large particles of mineral substrate. Particles or nutrients can be taken up by biological and physical processes in the bed, and then subsequently released back to the flow, resulting in cycling of particles between the bed and the flow in conjunction with downstream displacement. This pattern of coupled vertical cycling and downstream transport is known as "nutrient (or particle) spiralling" (Newbold et al. 2005). One important implication of nutrient spiralling is that it slows the downstream transport of nutrients, thus promoting primary production and biogeochemical processing within a given stream reach.

Humans can disrupt the natural patterns of stream dynamics by, for instance, installing dams to regulate flow and store water. These modified patterns rarely duplicate those naturally found at streams flowing from lakes (Richardson and Mackay 1991). This interruption of the longitudinal connections along the fluvial network is referred to as "serial discontinuity." This discontinuity can result in the interception of sediment and organic materials transported from upstream, alteration of flow and temperature regimes, changes in water chemistry, and suspended particulates.

SUMMARY

Streams and their riparian zones are complex systems that respond to transfers of water, sediment, nutrients, organic matter, and heat both laterally and longitudinally, all of which vary on time scales ranging from diurnal, synoptic (storm systems), and seasonal, to decadal and much longer. The current structure and function of a stream-riparian system reflects not only the influences of recent events but also those of past events and disturbances higher up in the stream network, which may be slowly propagating downstream. Because of the range of time scales associated with different types of disturbances and the rates at which different components of stream-riparian systems respond, it is inappropriate in many, if not most, cases to assume that stream structure and function are in a steady-state configuration (e.g., that the volume of instream wood is in equilibrium with long-term rates of input from the riparian forest). This dynamic nature of response to disturbances contributes to the spatial variability of stream conditions over a landscape, in addition to variations resulting from fundamental physiographic differences among catchments. This fact suggests that it may be difficult to use field measurements to

define reference conditions for use as management targets.

Significant advances have been made in our understanding of stream and riparian ecology over the last two decades, particularly in relation to organic-matter dynamics and the dynamics and function of instream wood. Nevertheless, significant gaps still exist that limit our ability to develop robust management guidelines.

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Salmonids and the Hydrologic and Geomorphic Features of Their Spawning Streams in British Columbia

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INTRODUCTION

The objective of this chapter is to describe some key linkages between the ecology of salmonid fish and the hydrologic and geomorphic features of their spawning streams in British Columbia. Salmonid refers to all species in the Salmonidae family of fishes, which includes Pacific salmon and trout (*Oncorhynchus* spp.), char (*Salvelinus* spp.), grayling (*Thymallus* spp.), whitefish and cisco (*Coregonus* spp.), Atlantic salmon and trout (*Salmo* spp.), inconnu (*Stenodus* spp.), and round whitefish (*Prosopium* spp.). The focus here is on Pacific salmon, trout, and char because of their widespread distribution in the province, their extensive use of stream habitats for spawning, and the volume of research devoted to these socio-economically important species. Stream-spawning salmonids and their reproductive success are affected by the hydrologic and geomorphic watershed processes that define and shape their streams and spawning habitats. To manage fish and land-use practices effectively, we need to understand how salmonid ecology and physical stream processes interact and are altered by natural and human disturbances in their watersheds.

The dependence of stream organisms on the quantity, quality, and movement of flowing waters has always been part of the underlying fabric of stream ecology. In the 35+ years since Hynes published his landmark book, *The Ecology of Running Waters* (Hynes 1972), appreciation for these hydrologic–biologic linkages has advanced considerably in North America, driven largely by the environmental movement and our increasing concern over the effects of land and water uses on fish and their habitat. Our understanding of specific ecological–hydrological processes and interactions in stream systems has progressed significantly. For example, we now recognize the ecological significance of hyporheic zones (See Chapter 13, "Stream and Riparian Ecology") where ground and surface waters mix below the streambed surface, creating important habitats for faunal communities (Edwards 1998). We also now recognize many of the dynamic and hydrologically mediated biochemical exchange processes that determine how nutrients and organic matter "spiral" downstream and are transformed and moved through stream ecosystems (Newbold et al. 1982). Woody debris is no longer "cleaned" from streams because it has been shown to be a critical physical element for stream morphology, fish and invertebrate habitats, and other important ecological functions (Bisson et al. 1987).

These advances in our knowledge have helped us better appreciate the importance of hydrologic and geomorphic processes to stream ecosystems and have aided in the development of more effective water and stream management policies. Nevertheless, significant gaps still exist in our knowledge of stream and watershed processes and of human impacts on the hydrology, morphology, and ecology of streams (Young 2000; Rosenau and Angelo 2003; Moola et al. 2004). For example, although small streams are ubiquitous throughout the province, only recently has the need been highlighted for better ecological data on their functions and roles in stream networks and the effects of natural and human watershed disturbances (Moore and Richardson 2003).

The Salmonid Landscape of British Columbia

British Columbia is a landscape of diverse geography, geology, vegetation, and climate that together define the physical and chemical characteristics of the streams and rivers draining the land. These stream characteristics in turn can define the fish species assemblages that have colonized and adapted to them. Salmonids exhibit various natural adaptations to the range of local stream conditions that reflect this diverse landscape.

The province encompasses a wide diversity of watersheds with markedly different geophysical and climatic conditions, ranging from the northern boreal mountains and taiga plains bordering the Yukon Territory to the near-desert valleys of the south Okanagan and the temperate coastal rainforests of the Coast and Vancouver Island. This diverse hydrologic and geomorphic landscape yields a variety of streams and rivers, ranging from the great Fraser, Skeena, Stikine, Columbia, and Mackenzie Rivers with their biologically diverse resident and migratory fish communities, to the ubiquitous first-order headwater streams and tributaries that feed all stream networks. The latter may serve as spawning and rearing ecosystems for species such as bull trout (*Salvelinus confluentus*) and cutthroat trout (*Oncorhynchus clarki*) (Gomi et al. 2002).

The coastal rainforests yield an abundance of warm-in-winter, soft-water streams that are important habitat for anadromous salmon, trout, and char (Rosenfeld et al. 2000). Perennially cold, glacially turbid streams can be found draining the glaciers and snowfields of the coastal and interior mountains. These streams present a challenging physical environment for many aquatic species (Lorenz and Filer 1989; Richards and Moore 2003). Overlaying this mosaic of stream ecosystems are the many streams and watersheds whose hydrologic and physical features have been modified by agriculture, forestry, urban development, mining, impoundment and flow regulation, diversions, dykes, and other human constructions.

Scope of the Chapter

This chapter illustrates how some of the natural hydrologic and geomorphic characteristics of streams can influence various aspects of the ecology of salmonids in their spawning streams. The emphasis is on the natural interactions between salmonids and their physical stream environment rather than the effects of human disturbances (see Chapter 7, "The Effects of Forest Disturbance on Hydrologic Processes and Watershed Response," Chapter 9, "Forest Management Effects on Hillslope Processes," and Chapter 15, "Riparian Management and Effects on Function"), highlighting the need to better understand the role watershed management plays in conserving the hydrologic and geomorphic features of salmonid spawning habitats.

This chapter focusses on the freshwater reproduction stages of salmonids, from the migration into spawning streams up to the emergence of fry. First, we look at how seasonal streamflows, determined by regional and seasonal variations in climate and hydrology, can affect spawner migrations. We next describe the importance of natural hydrologic and sedimentation processes in the creation of suitable stream substrates and habitats for salmonid spawning and egg incubation. We also discuss hydrologic effects on the survival of eggs and alevins. We then consider spawning salmon as geomorphic and ecologic disturbance agents in their own right, reworking and shaping the streambed for redd construction and enriching spawning streams. Lastly, we look at the relationship between streamflow and the emergence of salmonid fry from natal gravels.

The scope of this chapter is best viewed in the context of the small- to moderate-sized streams that make up the majority of the stream length in watersheds and where terrestrial–aquatic linkages are strongest (Gomi et al. 2002). These include first-order headwater and tributary streams up to larger third- and fourth-order streams and rivers. For a comprehensive description of large Pacific Northwest rivers, which includes physical characteristics, ecology, and management, the reader is referred to the excellent texts by Naiman and Bilby (editors, 1998) and Benke and Cushing (editors, 2005). Wetlands and floodplains are also not specifically addressed because their ecology has a unique dependence on local geomorphic and hydrologic conditions that is beyond the scope of this chapter (Brown 2002).

Stream research conducted in British Columbia has been driven largely by the need to better manage the effects of land disturbances such as forestry, agriculture, or urban development on stream ecosystems. Research conducted at the University of British Columbia's Malcolm Knapp Research Forest in the Fraser Valley (Kiffney et al. 2003), the Carnation Creek Watershed Study on the west coast of Vancouver Island (Hartman and Scrivener 1990; Tschaplinski 2000), and the Stuart-Takla Fish-Forestry Interaction Project in the north Fraser River watershed (MacIsaac [editor] 2003) are three examples of large-scale, multidisciplinary projects conducted in British Columbia that evaluate the impacts of forest management on stream ecology. These studies, along with many others in the province and elsewhere, have helped advance our knowledge of how hydrologic watershed processes affect the ecology of salmonid streams.

STREAMFLOW AND SPAWNER MIGRATIONS

The annual hydrograph of a British Columbia stream depends on the size, shape, elevation, and geographic location of its watershed along with the local climate, vegetation, and geology, all of which vary widely across the province. Seasonal flow regimes characteristic of different regions of British Columbia are discussed in greater detail in Chapter 4 ("Regional Hydrology"). Differences in seasonal flow patterns, along with the physical features of the channel, determine the types of stream organisms best able to utilize the habitat. Salmonid behaviour, physiology, and life history are adapted to a specific range and seasonal pattern of water and flow conditions. For example, juvenile coho (*O. kisutch*), steelhead (*O. mykiss*, anadromous rainbow trout), and cutthroat trout can co-occur in the same stream reaches (sympatric) but during low to moderate streamflows tend to segregate into microhabitats based partly on the hydraulic characteristics of different channel features (Bisson et al. 1988). Seasonally low streamflows can contract or fragment the available habitat into pools, and trigger the cessation of instream movements and foraging by juvenile salmonids (Mellina et al. 2005; Huusko et al. 2007). The size and frequency of freshets and the availability of suitable high-flow refuges are known to significantly affect the survival of juvenile coho in coastal British Columbia streams (Mason 1975; Brown and Hartman 1988; Shirvell 1994).

Hydrologic conditions in streams also affect the migration of adult salmonids to their spawning areas (Everest et al. 1985; Hodgson et al. 2006). Natural seasonal variations in streamflow, driven by local climate and precipitation and moderated by the hydrologic characteristics of the watershed, can affect both the timing of salmonid migrations and the accessibility of spawning locations. Low water levels during the spawning window can limit how much of the stream is accessible and useable for spawning. Obstructions (falls, canyons, beaver dams) can delay migration for adult salmon and may only be passable under high or low flows depending on the type of barrier (Sandercock 1991; Cooke et al. 2004; Rand et al. 2006). Streamflow can be an important cue for adults to enter spawning streams, and many salmon runs are known to delay entry at the mouth of a stream for a month or more waiting for rain to raise streamflows (Eames et al. 1981; Lister et al. 1981; Holtby et al. 1984). Coho with exceptionally early or late spawning stream entries are believed to be showing local adaptations to specific seasonal discharge patterns in order to ensure that flows are adequate for migration past stream obstructions (Sandercock 1991).

Water temperatures also play an important role in regulating the migratory timing and enroute survival of adult salmonids (Macdonald et al. 2000). Avoidance of high water temperatures may account for the early migration and extended holding of salmon populations in freshwater before maturation and spawning (Hodgson and Quinn 2002). The spawn timing of salmonid populations is thought to reflect the need of ensuring that egg incubation and fry emergence match local environmental and forage conditions which benefit juvenile survival (Brannon 1987). These population-specific adaptations of migration and spawn timing to environmental conditions are just part of the range of adaptations to local hydrologic conditions that salmonids exhibit.

For salmonid reproduction, the nature of the streambed is one of the most important geomorphic features of the stream. Salmonids generally spawn in streams from summer through spring, although some populations of chinook (*O. tshawytscha*) and steelhead spawn earlier. They incubate their eggs in redds dug into the streambed. Stream-specific hydrologic and geomorphic processes, including ground–surface water interactions, largely determine the location and quality of spawning sites in a stream. The natural scouring, sorting, and deposition of sediments by water and as affected by in-channel structures determine the spatial extent, depth, and size composition of gravel deposits within a stream. The dynamic hydrologic and geomorphic processes that create and maintain gravel deposits within a stream are discussed in Chapter 10 ("Channel Geomorphology: Fluvial Forms, Processes, and Forest Management Effects"). The quantity and quality of water flowing through the gravels is also an important factor determining the suitability of a site for nest construction and egg incubation.

Different species of salmonids spawn in different substrates with different hydrologic and physical characteristics. Some salmonids, such as fluvial Arctic grayling (*T. arcticus*) and mountain whitefish (*P. williamsoni*), do not dig nests in streambeds but are broadcast spawners, fertilizing and depositing their eggs among the natural sand and cobble substrates of the streambed rather than digging nests in the substrate. These eggs are more exposed to natural streamflow variations and bedload movements during incubation; however, most salmon, trout, and char dig nests or redds to fertilize, protect, and incubate their eggs. In the gravels, eggs develop into alevins, embryos with yolk sacs that are absorbed as they grow to the "swim-up" fry stage. These salmon generally choose spawning sites with the most favourable subsurface water flow and gravel conditions for the survival of the incubating eggs and development of the alevins. Egg-to-fry survival can range widely from less than a few percent to more than 70% (Groot and Margolis [editors] 1991). This extreme range in survival is in part a function of spawning bed quality, which is affected by annual and seasonal fluctuations in stream and intergravel flow conditions, by natural sediment infiltration that can affect incubation conditions in the gravels, and by the particle size distribution (e.g., median diameter, geometric mean) and percentage of fine sediments (e.g., < 0.85 mm diameter) of the incubation gravels (Chapman 1988; Young et al. 1991).

Fine sediments reduce intergravel water flows, decreasing the supply of dissolved oxygen to the eggs and alevins and the transport of ammonia and other metabolites away from the egg pockets. These sediments also inhibit alevin movement and fry emergence; if the organic content of the sediment is high, microbial processes will compete for oxygen with the developing eggs. Gravel quality is sensitive to natural and anthropogenic sediment generation and to transport processes in streams and their watersheds, both before spawning and during incubation. Annual and seasonal fluctuations in these processes can affect spawning success and egg-to-fry survivals.

The coarseness of spawning gravels is also important. Size of spawners is one of the factors that determines the size and depth of redds and the largest gravel sizes suitable for spawning substrates. Salmonids have a limited ability to move gravels using water currents generated by body flexing and tail movements. Streambeds may be "armoured" by large cobbles that spawners may not be able to excavate effectively. The maximum median diameter of spawning gravels utilized by a salmonid species is related to the size of the fish. Salmon are large-bodied salmonids and Kondolf (2000) found that the maximum median-size distribution of the gravels used by Pacific salmon for redd construction was a function of the length of fish (Figure 14.1).

Hyporheic zones are the porous streambed substrates in which surface water and groundwater mix and hydrologic, geochemical, and biological stream processes interact. Salmonids use hyporheic substrates for redd construction and egg incubation because of the good intergravel water flows, which supply oxygen and remove waste metabolites (Geist and Dauble 1998). This intergravel flowing water is typically a mixture of stream surface water forced into the streambed by upstream hydraulic gradients and groundwater upwelling from the surrounding catchment (Malcolm et al. 2005). Increases in water depth relative to variations in the streambed's geomorphic features and topography (e.g., pools and tail-outs) create localized increases in hydraulic pressure and surface water downwelling into porous streambed substrates.

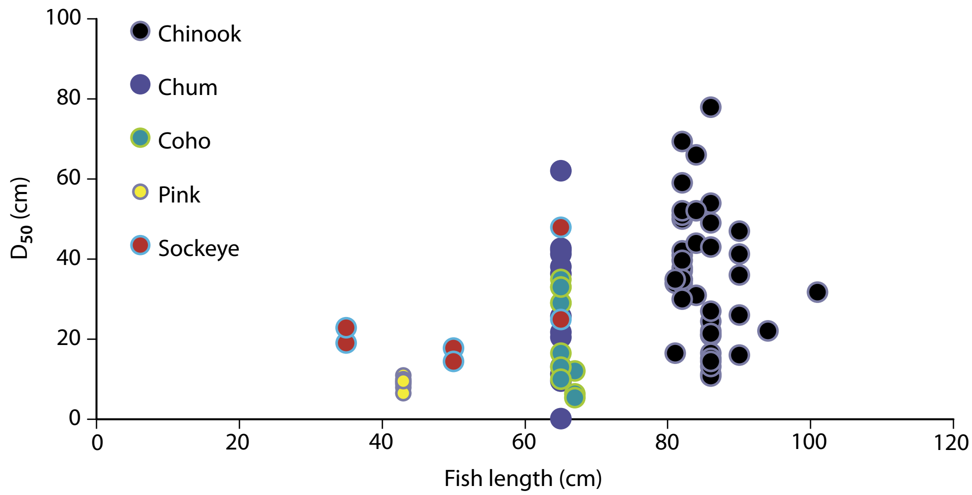

FIGURE 14.1 *Spawner size is related to the maximum median particle size of the spawning gravels utilized for redd construction. Here the average median diameter (D_{50}) of spawning gravel utilized is plotted against the average body length (cm) of female spawners for five species of Pacific salmon from data compiled by Kondolf and Wolman (1993).*

For egg deposition, female salmonids dig pits that are covered with gravels from another adjacent upstream pit to form a hump or tail spill. After digging and burying several pits and egg pockets, a large redd has a pool-riffle morphology that creates localized hydraulic gradients, enhancing downwelling and intergravel water flows through the egg pockets (Figure 14.2; Geist and Dauble 1998). Surface water flow into and out of the redd results from higher water depth and hydraulic pressure on the upstream pool side versus the downstream riffle side. Salmonid redd construction can significantly change local hydraulics; thus, high densities of large-bodied spawners can significantly modify channel bed morphology and intergravel flows.

The water quality of intergravel flow for incubating eggs (temperature, dissolved oxygen levels) depends on the relative contributions and qualities of the mixing surface and groundwater sources (Malcolm et al. 2005). Groundwater from the catchment may come from a considerable distance and its oxygen content is often a function of time spent below ground. Thus, the relative mixing of surface and ground waters can determine the temperature and oxygen quality of the intergravel water, affecting the development rates and survival of incubating eggs. Groundwater sources have relatively constant temperatures and oxygen content, whereas downwelled surface waters reflect seasonal changes in stream temperatures and oxygen levels.

The mixing of ground and surface water will vary seasonally with streamflow. During periods of high flow and deeper water, the rate of surface water downwelling will increase and this can dilute intergravel groundwater with surface water; groundwater may dominate the intergravel water during low flow periods. Groundwater upwelling sites can also be critical thermal refuges in winter when cold surface water makes warmer groundwater upwellings favourable habitat for egg incubation and alevin refuge. Variations in other ecologically important water quality parameters, such as ion chemistry and temperature, are also dependent on seasonal flows. Seasonal changes in the relative contributions of soil and groundwater sources to streamflow can manifest in seasonal variations in downstream water quality (Constantz 1998; Feller 2005; Chapter 13, "Stream and Riparian Ecology").

The physical and chemical cues used by salmon and trout to actively identify redd sites with suitable intergravel water flow, oxygen, and temperature conditions are not entirely clear (Kondolf and Wolman 1993; Quinn et al. 2006). Salmon are capable of homing to small-scale natal habitats so natural selective pressures may ensure that the majority of spawners return to suitable gravel areas. Alternatively, salmonids may be able to sense the movement and quality of upwelling water using olfactory and other clues. For example, Cope and Macdonald (1998) found that sockeye salmon rarely dig redds in marginal habitats

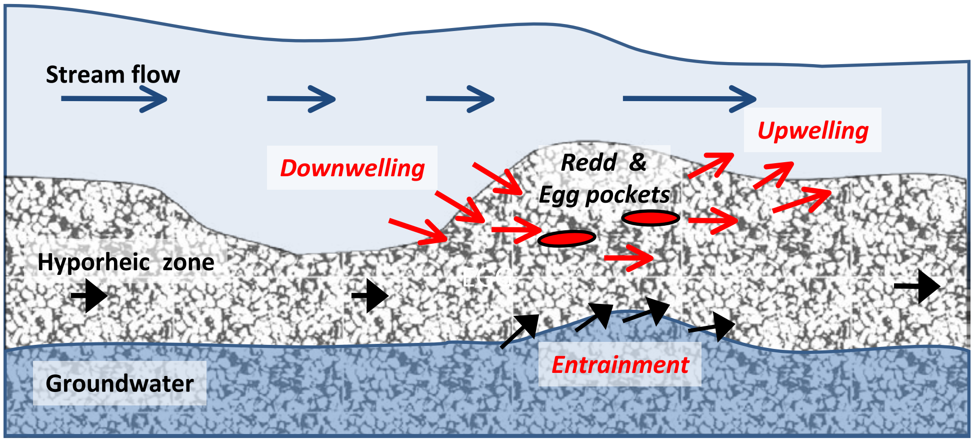

FIGURE 14.2 *Schematic of intergravel water flow through a salmonid redd. Redd morphology changes the streambed topography and water depths over the redd, creating upstream hydraulic gradients that force surface water to downwell through the redd and upwell on the downstream side. Entrainment of groundwater may occur. (Adapted from Geist and Dauble 1998)*

where intergravel oxygen levels are near or below 3 mg/L.

Accessible areas with suitable gravel and hyporheic flow conditions for successful salmonid spawning may be a small part of the total stream area. Identifying and protecting these spawning habitats is an important part of conservation efforts for many salmon, trout, and char in British Columbia. Attempts to model and predict the locations of these spawning habitats use physical stream and watershed characteristics (spawning habitat suitability models; e.g., Shirvell 1989). However, although physical features such as gradients, channel morphology, and water depth are readily measured, properties such as gravel quality, intergravel water flows, groundwater upwelling, and subsurface water quality are not as easily measured or predicted from physical stream and watershed features (e.g., Geist and Dauble 1998; McHugh and Budy 2004). In addition, the fidelity of spawners to their specific natal areas can only be accounted for by field surveys to determine the full use of a stream by resident salmonids.

Scouring Flows

Another important aspect of the geomorphology and flow regime of streams for salmonid egg and alevin survival is the frequency and magnitude of scouring flows during the egg incubation and alevin stages. Scour and fill processes are a natural part of salmonid streams and create important channel features such as riffles, pools, and side channels. These processes build, clean, and sort alluvial gravel deposits that serve as salmonid spawning areas; however, if the depth of streambed scour exceeds the depth of egg burial, then rare high flow events may reduce survival of specific year-classes of salmonids (Kondolf et al. 1993). Coastal streams are particularly prone to extreme winter flow events from Pacific Ocean storms (Chapter 4, "Regional Hydrology"). These events can be responsible for substantial bedload movements and the scour of redd egg pockets with losses of eggs and alevins (Tripp and Poulin 1992; Montgomery et al. 1996). Theses losses may be a significant part of the high, natural mortalities salmonids experience at this life stage (Kondolf et al. 1993).

The risk of scouring flows depends on the climate, the hydrologic characteristics of the watershed (e.g., upstream lakes that can buffer peak flows), the morphometry of the stream channel, the volume and type of woody debris in the channel, and the sizes and types of substrate (e.g., alluvial gravels). Scour and fill sites are very localized. The susceptibility of a specific spawning bed to scour depends on reach conditions such as streambed shear stresses, which are a function of local channel morphology and flow, and the particle entrainability of the bed material (e.g., substrate size and embeddedness; Rennie and Millar 2000). Different reaches within the same stream can have different scouring rates that correspond to unique flow and geomorphic characteristics.

The depth at which a salmonid species buries its eggs is correlated to the size of the female and the median substrate size (DeVries 1997). Maximum redd depths can range from 10 cm for small kokanee (*O. nerka*) to more than 50 cm for large chinook (Figure 14.3). The shallower the egg pocket, the more susceptible it is to scour during freshets. Shallower redd depths result from smaller females, larger substrate sizes, or spawners encountering excavation barriers (e.g., large rocks, hard-pack clay, or clay pans) at depth in their spawning streams.

Montgomery et al. (1996) suggested that gravel scour depths may limit the species and sizes of salmonids that can utilize a habitat by selecting for those that dig to redd depths exceeding the average scour depth in a stream. It seems reasonable to conclude that if a stream experiences frequent bed-scouring events, only salmonids that can bury eggs at or below the maximum depths of bed scour will be able to sustain runs to a stream; however, it is not yet known whether stream scour plays a significant role in the zoogeography of British Columbia salmonids (van den Berghe and Gross 1984).

Low Flows

Periods of low flow occur naturally in streams, during late summer and early autumn for coastal streams and late summer through winter in snowmelt-dominated watersheds typical of the interior. Low flows can affect salmonids at any freshwater stage. During these times of year, streamflow is primarily sustained by groundwater. The frequency, magnitude, and duration of low flow events in a stream depend on regional and annual climate variations, the hydrologic properties of its watershed, and the hydrology and geomorphology of the stream (Chapter 4, "Regional Hydrology," Chapter 6, "Hydrologic Processes and Watershed Response," and Chapter 10, "Channel Geomorphology: Fluvial Forms, Processes, and Forest Management Effects"). Dry channels and periods of low flow are common higher up in watersheds where groundwater discharge to streams is minimal. Although surface

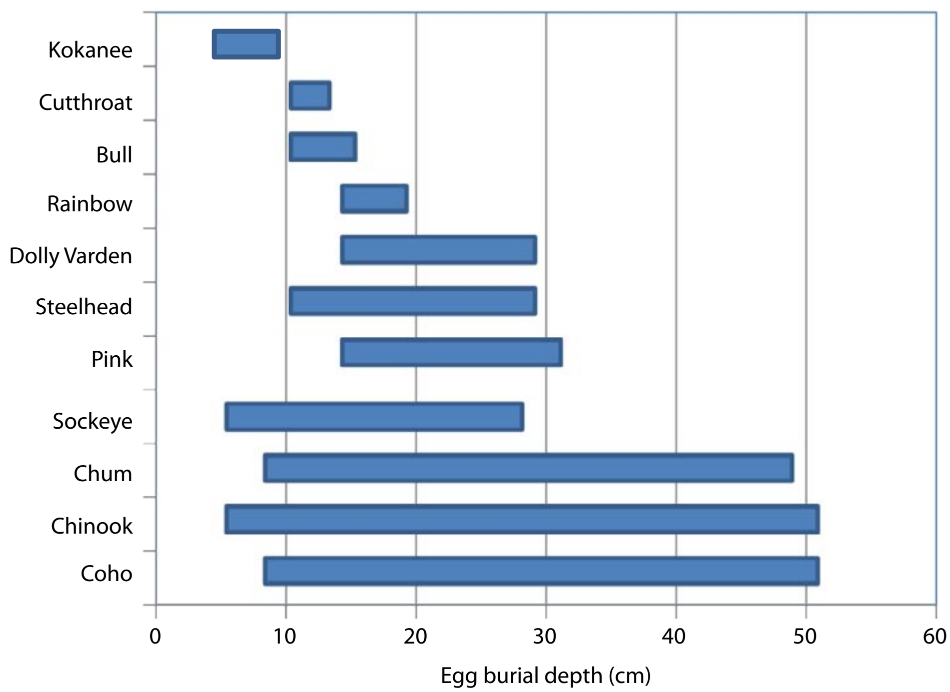

FIGURE 14.3 *Egg burial depths (cm) for different salmonids measured from original streambed level to top of first egg pocket. The smallest spawners (kokanee) have the shallowest redd depths and the largest salmon (chinook) have the deepest and most variable redd depths. Egg burial depths are indicators of egg-pocket vulnerability to scouring flows and gravel disturbance. (Data from DeVries 1997)*

water may be limited during low flow periods, considerable subsurface (hyporheic) water flow can still occur through the streambed, particularly in alluvial reaches with permeable substrates.

Spawning beds that had adequate water levels during spawning may experience lower water levels during egg and alevin incubation. Low flows over winter can strand redds, exposing the eggs and alevins to desiccation or freezing, which reduces egg-to-fry survival. Alevins can move down in the gravels to avoid desiccation and freezing when water levels drop (Dill 1969). Cope and Macdonald (1998) reported that sockeye alevins in interior British Columbia streams, where freezing and ice penetration into the gravels can occur during winter, were capable of moving down in the gravels to avoid ice formed in the surface gravels (Figure 14.4). This behaviour may be a local adaptation to interior climates and stream conditions. The ability of alevins to move within the gravels and avoid ice would confer a significant survival advantage. However, this advantage may be lost if the intergravel water becomes dominated by groundwater lacking sufficient oxygen for alevin survival (Whitfield and McNaughton 1986).

Low flows that progress to intermittent flows result in spatially discontinuous habitats. As the stream channel breaks into discrete pools, riffle habitats disappear, temperature and oxygen levels in the intergravel water and pools are altered, and fish and stream biota are affected. Unless the natural hydrologic properties of the stream and watershed have recently changed or an unusually extreme climate event (e.g., drought) occurs, the salmonid communities utilizing the watershed will have life histories and behaviours adapted to an intermittent flow environment. Bradford and Heinonen (2008) reviewed much of the literature on the effects of low flows on stream biota in the context of water regulation and diversion. They concluded that many potential responses by fish and invertebrate communities to low flow events are possible and that many of these responses were stream- or reach-specific, driven by local hydrologic, geomorphic, and climate conditions acting on different species assemblages.

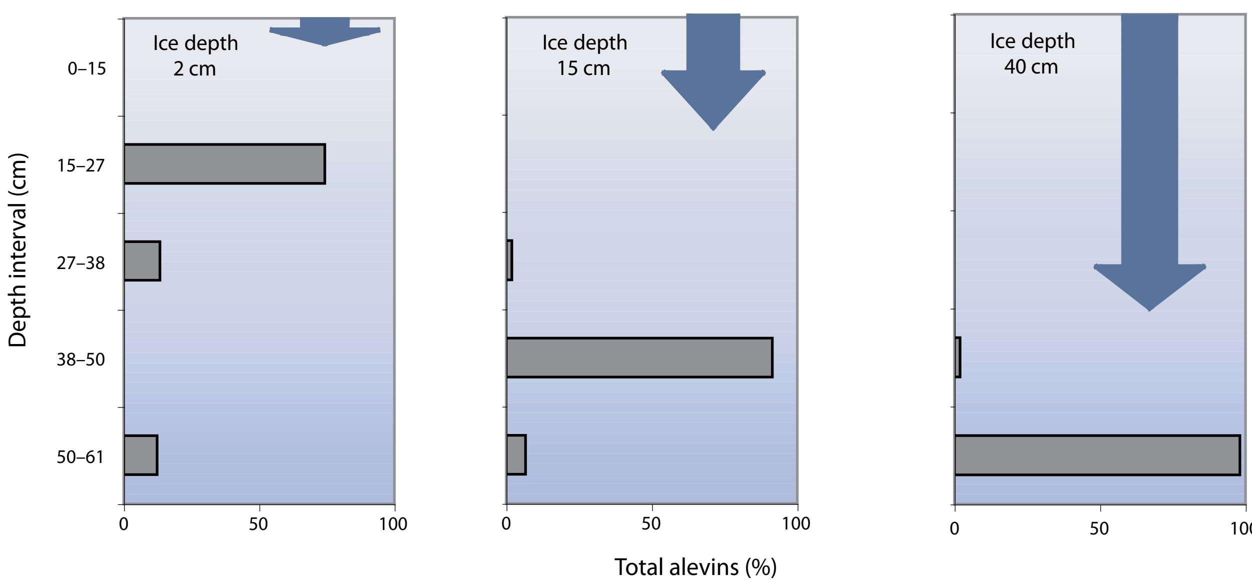

FIGURE 14.4 *After hatching, sockeye salmon alevins from interior British Columbia streams can move within the gravels and migrate downward to avoid ice formation in the surface gravels. Fertilized eggs were placed at 20 cm in capsules buried in stream gravels subject to different levels of freezing and recovered in February 1994. Alevins avoided ice penetrations of 2, 15, and 40 cm into the surface gravels by moving down to depths greater than 50 cm in the gravel bed. (Data from Cope 1996)*

Salmonids that spawn at high densities in streams can significantly disturb the streambed during redd construction (Gottesfeld et al. 2004; Hassan et al. 2008). Excavation of redds reduces the fine sediment content of gravels, improving conditions for intergravel flows and egg incubation, and raising suspended sediment concentrations in streams during spawning (Kondolf et al. 1993; Cheong et al. 1995). In the course of constructing their redds, salmonids can move volumes of coarse sediments short distances downstream. The scale of this streambed bioturbation depends on the species, female size, number and density of spawning salmon, and areal extent of the spawning beds in the stream. In some stream reaches, salmonids returning to natal gravels can result in major geomorphic disturbance. Hassan et al. (2008) estimated that mass spawning of sockeye salmon in four streams in the upper Fraser River watershed accounted for almost half of the annual bedload movement in the stream reaches where the salmon spawned. This is remarkable from a watershed perspective, given that the abundance of sockeye salmon in streams in the Fraser River watershed in the late 1800s may have been up to two orders of magnitude greater than current escapements (Ricker 1987). The growth of the commercial fishing industry and migration blockages at Hell's Gate significantly reduced escapements of sockeye and other salmon species to the Fraser River; the current impact of salmon on the geomorphic processes of spawning streams is likely just a shadow of the pre-European condition.

Mass spawning can create streambed forms that persist from year to year (Montgomery et al. 1996). One of the most graphic examples of this type of geomorphic disturbance and reworking of streambeds by spawning salmonids can be seen in the spawning "dunes" and other patterns of streambed disturbance created by chinook salmon in British Columbia streams. Gottesfeld et al. (2008) discussed the bioturbation impacts of salmon in detail and identified 25 stream locations in British Columbia where the dune streambed forms of chinook salmon are evident. Dunes are formed when spawning gravels are shaped by redd digging, which creates submerged, dune-shaped gravel deposits in the alluvial gravels of some large rivers such as the upper Nechako, Harrison, upper Babine, and the upper Chilko (Gottesfeld et al. 2008). Successive redd excavations and egg pocket burials combined with strong river currents create gravel bars perpendicular to the flow of the river that reach over 0.5 m high and over 10 m long (Figure 14.5). The dunes are a persistent feature of the streambeds maintained by annual spawning and these structures may provide a partial refuge from the current for holding adults and active spawning pairs. In other chinook spawning sites such as the South Thompson River, redd digging can create a streambed form of submerged pool-riffle patches readily visible from the air (Figure 14.6).

Large runs of spawning salmonids can be a significant disturbance force for the streambed and its benthic and hyporheic biota which can have a significant impact on stream ecology. Moore et al. (2004) found that spawning sockeye reduced the volume and percentage of fine sediments in the streambed after redd digging and reduced the periphyton (attached algae) biomass of the streambed by 80%. Moore et al. (2004) also noted a decline in most benthic invertebrate taxa in spawning areas. Peterson and Foote (2000) measured a significant increase in invertebrate drift during spawning, a common disturbance response by the invertebrate community. They reported that the magnitude of spawner influence on the benthic communities depended on spawner density. Moore et al. (2004) also found some displacement of invertebrate taxa to non-spawning areas.

An aerial view illustrates an example of the extent of streambed scouring caused by sockeye salmon spawning in the Lower Shuswap River (Figure 14.7). Much of the streambed's dark periphyton and biofilm has been scoured or buried by the digging actions of the spawning salmon, and redd locations are readily visible. Periphyton and biofilms are an important contributor of primary organic matter production to stream food webs, and the disturbance and reduction of periphyton biomass could have a short-term effect on spawning stream productivity.

Although salmonids may negatively and temporarily affect the biomass of benthic flora and fauna by physical disturbance during spawning, the environment is also subsequently enriched during spawning and after death. Anadromous salmon, as major vectors of marine-derived nutrients and organic matter, may be important in maintaining the productivity and biodiversity of spawning streams for their progeny and other aquatic and terrestrial

FIGURE 14.5 *Chinook salmon spawning "dunes" in the Harrison River (2004), illustrating the effect chinook spawners can have on streambed form. (Photo: A. Gottesfeld)*

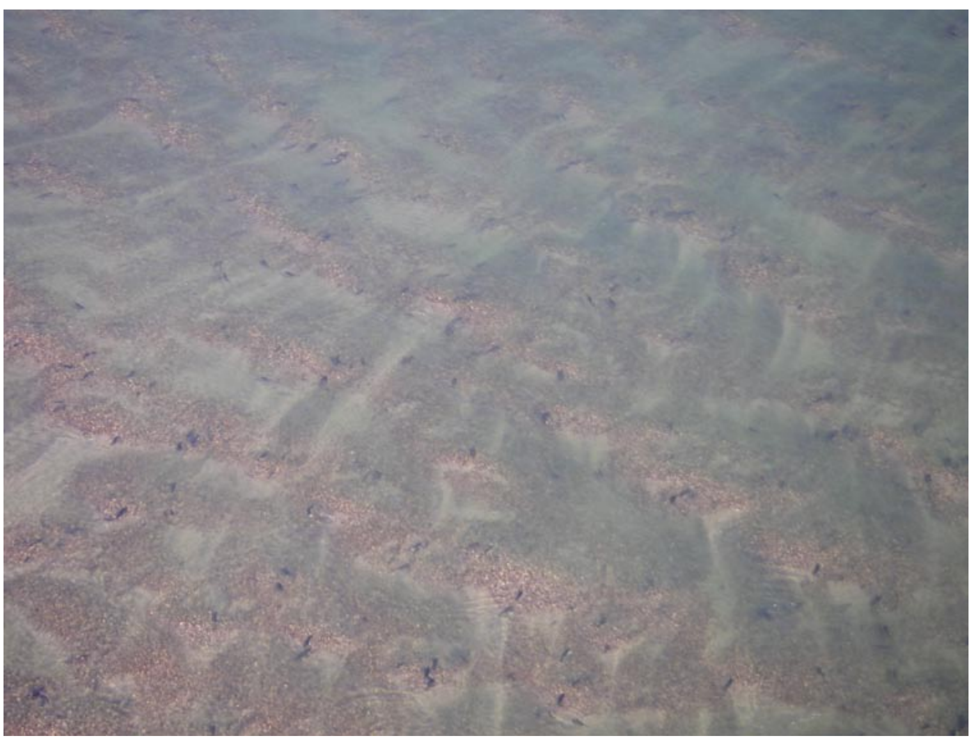

FIGURE 14.6 *Mosaic of submerged pool-riffle patches created by chinook redd construction in the South Thompson River (2006). (Photo: R. Bailey)*

FIGURE 14.7 *Sockeye salmon spawning area in the Lower Shuswap River (2006), illustrating the scouring of periphyton from the surface gravels and the amount of streambed disturbance caused by redd digging. (Photo: R. Bailey)*

biota (Gende et al. 2002; Schindler et al. 2003; Chapter 13, "Stream and Riparian Ecology"). Organic matter and nutrients released as excreta and gametes during spawning and the decomposition of carcasses can enhance periphyton and biofilm production and some benthic invertebrates (Peterson and Foote 2000; Johnston et al. 2004). Periphyton, bacterial biofilms, and benthic invertebrate densities have all been shown to increase in streams supplemented with salmon carcasses (Wipfli et al. 1998; Fisher Wold and Hershey 1999). Bilby et al. (1998) found that the addition of salmon carcasses to a stream benefitted the growth of juvenile salmonids that directly utilized the eggs and carcasses of spawners. Currently, this nutrient and energy subsidy, similar to the bioturbation of stream geomorphology, is likely also just a shadow of the subsidy provided by pre-European salmon populations to British Columbia salmonid spawning streams.

ALEVINS AND FRY EMERGENCE

The rate and timing of egg development to the fry stage strongly depends on water temperature. Many useful predictive models for adult spawn timing, egg hatch, and fry emigration are based in part on the accumulation of thermal units by developing eggs and embryos (e.g., Beer and Anderson 1997). After yolk absorption is complete, the fry must emerge from the gravels and begin free-feeding or move to rearing habitats to feed (Brannon 1987). Emergence before complete yolk absorption is not uncommon, but these fry may be more susceptible to predation and displacement by currents because of limited swimming ability. The early movements and migrations by emergent fry are important adaptive behaviours, allowing juvenile fish to exploit different habitats to increase their growth and survival (Kahler et al. 2001); however, the patterns and timings of emergence and early movement for fry vary greatly among different salmonid species and populations.

Sockeye salmon fry emerge in spawning streams during the spring and most move downstream or upstream (e.g., Chilko Lake) to lake-rearing habitats (Raleigh 1971). "Taxis" refers to the directional movement exhibited by animals toward or away from an external stimulus. Fry from populations migrating downstream usually exhibit marked negative phototaxis (light) and negative rheotaxis (current) during the migration, moving after dark and with the current, often aggregating and holding during daylight hours along the margins of the streams where currents are weakest (Brannon 1972). Fry that migrate downstream can use currents to assist with dispersal; populations migrating upstream use the circulating eddy currents along the streambank to assist with movement. This relationship between current direction and velocity and fry movement is an innate heritable behaviour for salmonids (Raleigh 1971).

Brannon (1972) demonstrated the roles that spawn timing, incubation temperature, and genetic adaptation play in synchronizing sockeye fry emergence with environmental conditions, such as stream discharge and the availability of invertebrate food in a downstream lake. Fry emergence and downstream migration coinciding with high stream discharges may be a behavioural strategy that offers both energetic and predator avoidance benefits (Ginetz and Larkin 1976; Beauchamp 1995; Brännäs 1995), although movement during very high discharges might increase the risks of mortality from displacement into unsuitable habitats or from physical shock. McDonald (1960) and Tabor et al. (2004) suggested that spatial separation could occur between predators and prey when sockeye occupy and migrate in faster water and predators such as cottids (sculpins) stay in slower water close to the substrate. Stream discharge of Gluskie Creek in the upper Fraser River watershed, like most interior streams, is dominated by spring snowmelt. Significant annual variations are evident in the shape of its hydrograph and the timing of high flow events (Figure 14.8). Sockeye fry emigration from the creek commences when streamflows and temperatures begin to rise during spring melt, but the peak of migration does not always coincide with peak flows. Fry generally migrate from the creek during high water but before the peak in flow. Although rising stream discharge will increase hydraulic pressures in the gravels, it is not known whether salmonid fry can use pressure-sensitive cues to adapt emergence behaviour and timing to flow conditions.

The emerging fry of other salmonid species may disperse short distances to neighbouring rearing habitats within the stream or exhibit extensive upstream and downstream migrations. Coho salmon, cutthroat trout, rainbow and steelhead trout, and bull trout fry can all exhibit upstream migrations into smaller stream-rearing habitats. For these fry, emergence and movement during a time of high stream discharge could be a disadvantage that risks downstream displacement to less suitable habitats. The fry of salmonids that spawn in late spring, such as rainbow and bull trout, have less risk of encountering seasonably high discharges during summer emergence, whereas the fry of coastal fall and winter spawners, such as coho and steelhead, may be the most likely to encounter higher flow conditions during spring emergence.

Salmonid fry that emerge and remain among the gravel and cobble substrate to feed or that migrate upstream to new habitats must contend with stream currents. Fry taking refuge among the gravels must rise up in the current to feed. The swimming speed of juvenile salmonids is directly related to body length, increasing as the fish grow (Glova and McInerney 1977). As fry grow, their maximum sustained and critical swimming speeds increase, making the newly emergent fry the life stage most vulnerable to displacement caused by exposure to high stream discharges. Swimming speeds also depend on temperature, increasing with higher water temperatures, so both discharge and water temperatures interact (Glova and McInerney 1977).

Small, newly emerged salmonid fry cannot maintain position in a stream channel above critical water velocities and are susceptible to downstream displacement (Irvine 1986; Heggenes and Traaen 1988). Sustained swim speeds are those that fish can maintain against a current without fatigue. Critical swimming speeds are the maximum that can be sustained for a specific period of time, and can approximate the maximum sustained swimming speeds for salmonids (Beamish 1978). However, few measurements have been taken of critical speeds for newly emergent salmonid fry, particularly for many salmonid species common to British Columbia. Irvine (1986) found that downstream emigration of chinook salmon fry increased when peak water velocity exceeded 0.25 m/s. Ottaway and Clarke (1981) similarly found that water velocities exceeding 0.27 m/s affected the downstream movement of brown trout

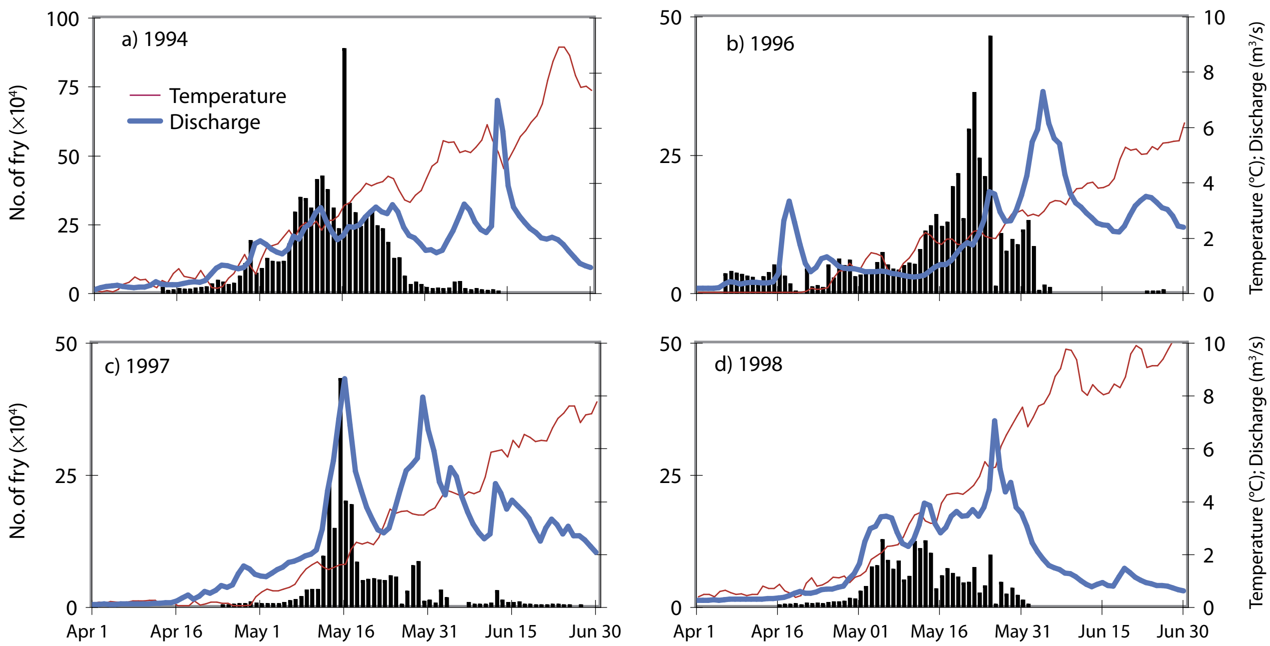

FIGURE 14.8 *Sockeye salmon fry emigration from Gluskie Creek always coincided with increasing spring discharges and water temperatures, but not always with the timing of peak flow events. Graphs show fry emigration (bars, #), water temperature (red line, °C), and discharge (blue line, m^3/s) in spring for Gluskie Creek during four different freshet regimes over 4 years. Adult sockeye escapements ranged from 22 116 to 9293 spawners.*

fry. Heggenes and Traaen (1988) found that critical velocities above 0.1 m/s could displace the "swim up" fry stages of Atlantic salmon, brook trout, brown trout, and lake trout from experimental troughs. The much lower critical velocities measured by Heggenes and Traaen (1988) were in smooth-bottomed troughs with velocities measured near the bottom; the other studies used gravel-bottomed troughs with velocities measured higher in the water column. As with natural streams, rough gravel and cobble substrates slow near-bed currents and provide interstitial velocity refuges for fry (Statzner et al. 1988).

SUMMARY

From the migration of adult spawners to fry emergence, salmonids illustrate many linkages between their ecology and the watershed-dependent hydrologic and geomorphic features of their spawning streams. Resident and anadromous salmonids exhibit local adaptations, allowing them to exploit particular spawning stream environments and successfully reproduce. Salmonid survival requires life histories and behaviours that correspond to specific features of the annual hydrograph and local instream hydrologic and streambed characteristics that benefit juvenile survival and egg incubation success. Salmonids can also alter their spawning and incubating environment and when spawning in large numbers are a formidable geomorphic agent.

Although alteration of natural hydrologic and geomorphic processes in watersheds by human land use, climate change, or natural disturbance and the ensuing impacts on stream and salmonid ecology are not the subject of this chapter, some of the potential implications can be inferred from the topics discussed. For example, clearcut logging, urbanization, forest fires, and widespread insect infestation can each alter features of a stream's annual hydrograph such as the magnitude, duration, and timing of peak flows and low flows (Chapter 7, "The Effects of Forest Disturbance on Hydrologic Processes and Watershed Response"). Changes to the hydraulic environment of the stream in turn will affect salmonid survival, including:

- adult migration timing and access to spawning habitat;
- surface-water downwelling and intergravel flows through redds;
- the risk of downstream fry displacement at emergence;
- fry survival during downstream dispersal; and
- the risk of redd scouring and siltation affecting egg and alevin survival.

The directions and magnitudes of these effects will depend on the unique hydrologic responses of the watershed to disturbance and the weather.

Healthy salmon, trout, and char populations have become synonymous with healthy aquatic ecosystems. Watershed processes influence the hydraulic and sediment properties of streams, which in turn affect the quality of the habitat for fish; however, these linkages can be complex and difficult to incorporate into management. Providing effective management direction for a given watershed requires a level of detail about watershed processes that is not trivial, but this may be required to successfully conserve the aquatic values of the watershed's streams.

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Riparian Management and Effects on Function

PETER J. TSCHAPLINSKI AND ROBIN G. PIKE

INTRODUCTION: RIPARIAN MANAGEMENT IN BRITISH COLUMBIA

Riparian Ecotones: Functions and Values

Riparian areas are the complex interface between aquatic and terrestrial environments within watersheds. These areas have been described as three-dimensional ecotones of interaction that include terrestrial and aquatic ecosystems, and that extend down into the groundwater, up above the forest canopy, outward across the floodplain, laterally into the near-slopes to various distances into terrestrial areas, and along watercourses at variable widths (Ilhardt et al. 2000).

Riparian meadows and forests extend from the smallest headwater tributaries to the mouths of the highest-order streams within watersheds. A riparian zone thus forms the key boundary that moderates all hydrological, geomorphological, and biological processes associated with this interconnected fluvial corridor (Swanson et al. 1988; Figure 15.1). Streamside zones are highly vulnerable to disturbance from processes and events occurring upslope and upstream because of the relatively small size of these zones and the extensive longitudinal and lateral connections with associated aquatic and terrestrial ecosystems (Swanson et al. 1988). These areas maintain ecological linkages throughout the forest landscape, connecting hillsides to streams and upper headwaters to lower valley bottoms (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a). No other landscape features within forests provide linkages that are as extensive and complex as those provided by riparian ecotones.

Riparian areas contain and support many of the highest-value resources in natural forests (Hartman and Scrivener 1990). The plant and animal communities in riparian areas frequently have the highest species richness found in forests (Gregory et al. 1991). Riparian habitats are also critical for several obligate species and for numerous others that use riparian areas for home ranges, travel corridors, and other purposes for at least a part of their life histories (McComb 1989). Raedeke (1988) indicated that 60% of the 480 species of wildlife in Washington State are found in wooded riparian habitats; 68 species of these mammals, birds, amphibians, and reptiles require riparian ecosystems to satisfy a vital habitat need during all or part of the year; and 103 species achieve their maximum abundance in riparian zones.

Streamside riparian areas may contain excellent growing sites for trees (Mouw and Dixson 2008). At the same time, these areas support aquatic ecosystems and associated fish populations through several functions (see Chapter 13, "Stream and Riparian Ecology," and Chapter 14, "Salmonids and the Hydrologic and Geomorphic Features of Their Spawning Streams in British Columbia"). Riparian vegetation stabilizes streambanks, provides shade to help regulate stream temperatures, provides a source of wood ("large woody debris" or LWD) for stream

FIGURE 15.1 *The riparian zone forms the key boundary that moderates all hydrological, geomorphological, and biological processes associated with interconnected fluvial corridors. Class S1 stream shown with riparian reserve. (Photo: R.G. Pike)*

channels, and supplies both organic detritus (leaves, twigs, and other plant material) that drives aquatic food webs and terrestrial invertebrates that serve as a direct source of food for fish (Gregory et al. 1991; Naiman and Décamps 1997; Naiman et al. 2000).

Although a significant amount of riparian research has been undertaken in the past 30 years, the debate about how to best manage these areas continues to dominate current riparian management in British Columbia and elsewhere. This is no wonder, given the intrinsic values riparian areas provide, and the diversity of riparian types and functions across the province.

The multitude of riparian values is at the centre of this debate because these values not only represent important ecological and environmental services, but also economic and social opportunities. For example, some stakeholders are concerned that certain levels of riparian protection will result in losses of forestry opportunities, wood and wood products, water withdrawals for agriculture and domestic use, grazing and cropland, access to minerals and mining, and freedom to manage private land (Verry 2000). Representatives of other interests believe that riparian areas require sufficient protection to avoid impacts to water quality and quantity, fish populations and habitat, native plant and animal species and communities, opportunities for recreation, aesthetic values, hydrological connections within watersheds, and ecological connections within watersheds and across landscapes. Riparian management often attempts to strike a balance among these often competing domains.

Legislation and Regulations in British Columbia

In British Columbia, several legislative statutes apply when working in and around water and, consequently, riparian areas. The *Water Act* regulates changes in or around streams to ensure that water quality, water quantity, fish and wildlife habitat, and the rights of licensed water users are not compromised. The *Water Act* applies to all streams regardless of the presence or absence of fish. Provisions under the *Water Act* are currently administered by the British Columbia Ministry of Environment. Federally, Fisheries and Oceans Canada has responsibility for all fish and fish habitat in Canada. The federal *Fisheries Act* prohibits the harmful alteration, destruction, or disruption of fish and fish habitat, as well as the deposition of deleterious substances in fish-bearing waters. For further details from the *Fisheries Act*, go to: http://laws.justice.gc.ca/en/ShowFullDoc/cs/F-14/.

The *Fish Protection Act* and the Riparian Areas Regulation are two additional legislative tools used to protect fish and fish habitat in British Columbia. The four major objectives of this Act are to: (1) ensure sufficient water for fish; (2) protect and restore fish habitat; (3) improve riparian protection and enhancement; and (4) strengthen local government powers in environmental planning. It works in concert with the *Water Act* to cover areas not fully addressed through existing legislation. The Riparian Areas Regulation was enacted under the *Fish Protection Act* to ensure that local governments protect riparian areas during residential, commercial, and industrial development. It is used for urban riparian management and does not apply to agriculture, mining, or forestry-related land uses.

Two provincial statutes apply specifically to forestry practices, including riparian management, on the timber harvesting land base. The *Private Managed Forest Land Act* applies to activities conducted on privately owned (non-Crown) forest lands, whereas the *Forest and Range Practices Act* (FRPA) and its predecessor, the *Forest Practices Code of British Columbia Act*, apply to all activities on Crown land in British Columbia including privately owned portions of Tree Farm Licences. In this chapter, we focus on the riparian management provisions under the latter two statutes. Knowledge of riparian management under the FRPA and FPC is important because many of the riparian provisions within the current results-based FRPA have been retained from the prescriptive FPC as default approaches in regulation.

This chapter provides a summary of the different riparian management systems and practices applied in British Columbia's forested watersheds. We discuss how forest management is conducted and how it can potentially affect riparian areas, streams, and fish habitats. We conclude with a summary of current efforts to evaluate the effectiveness of riparian management practices in British Columbia.

RIPARIAN MANAGEMENT OBJECTIVES AND FRAMEWORK

Objectives, Values, and Principles

Recommendations for ecosystem-based approaches to riparian management have been advanced since the early 1990s (Gregory et al. 1991; Forest Stewardship Council 2005; Richardson et al. 2005). However, all jurisdictions in the Pacific Northwest of North America use fish as the principal, if not dominant, foundation for riparian management in forested areas. For example, the Forest Stewardship Council of Canada's riparian standards address various environmental values and ecosystem processes at watershed and site scales, but retain fish presence or absence as the main determinant for its stream classification and management system (Forest Stewardship Council 2005). Water for domestic use is the other most frequently identified management objective in the Pacific Northwest and elsewhere in North America.

No scientifically sound basis exists for managing riparian and aquatic values on the presence of game fish alone. Nevertheless, some jurisdictions, such as the State of Alaska and the United States Department of Agriculture Forest Service Region 10 (Alaska), explicitly emphasize the importance of anadromous salmonids or "high-value" resident fish (i.e., trout and char) and require higher levels of protection for waters used by these species. The foundation for determining riparian practices in British Columbia is largely fish-based (see next section), but riparian management objectives generally encompass a broader, watershed-process perspective to maintain and protect riparian functions. For example, objectives for managing riparian areas under the FPC looked beyond a fish-focussed view and were implemented to:

1. minimize or prevent impacts of forest and range uses on stream-channel dynamics, aquatic ecosystems, and water quality of all streams, lakes, and wetlands;
2. minimize or prevent impacts of forest and range use on the diversity, productivity, and sustainability of wildlife habitat and vegetation adjacent to streams, lakes, and wetlands with reserve zones, or where high wildlife values are present; and

3. allow for forest and range use consistent with 1 and 2 above (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a).

These principles remain consistent with the objective set by government in FRPA's Forest Planning and Practices Regulation (FPPR) for water, fish, wildlife, and biodiversity within riparian areas, which is: "without unduly reducing the supply of timber from British Columbia's forests, to conserve, at the landscape level, the water quality, fish habitat, wildlife habitat and biodiversity associated with those riparian areas" (Forest Planning and Practices Regulation).

Riparian management objectives vary broadly across the Pacific Northwest. In federally managed forests in the United States (i.e., USDA Forest Service Region 6), riparian management is focussed on the protection and enhancement of riparian ecosystems and habitats for species that rely on late-successional and old-growth forests (e.g., Northern Spotted Owl), and for the Aquatic Conservation Strategy in the Northwest Forest Plan (see Tuchmann et al. 1996). Accordingly, conservative riparian provisions are in place to ensure compliance with the United States *Endangered Species Act* and the *Clean Water Act*. In Oregon and Washington, tree retention targets in riparian management zones have been based on multiple objectives around managing for riparian and aquatic values, riparian ecosystem functions, and rehabilitating inadequately stocked forest stands (Adams 1996; Oregon Secretary of State 2010a, 2010b; Washington State Department of Natural Resources 2010).

Classification of Streams, Lakes, and Wetlands in British Columbia

Before we describe the different riparian management systems used in British Columbia, it is useful to summarize the water-body classification system used in forestry management, and to review some of the commonly used terms and concepts associated with both the FPC and FRPA approaches for streams, lakes, and wetlands.

The principal management unit is the riparian management area (RMA), which has been in continuous and consistent use across the province since 1995. This unit consists of a riparian management zone (RMZ) and, sometimes, a no-harvest riparian reserve zone (RRZ) located immediately adjacent to the water body (Figures 15.2, and 15.3). The widths of

FIGURE 15.2 *Riparian management area tree retention by basal area applied within 10 m of a small stream. (Photo: R.G. Pike)*

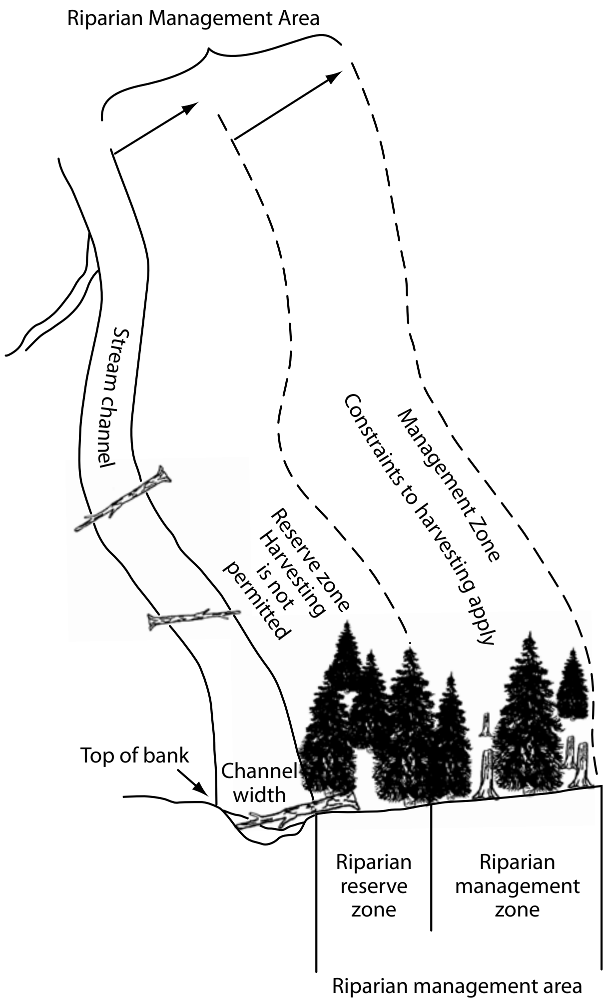

FIGURE 15.3 *Riparian management area for streams showing a management zone and a reserve zone along the stream channel (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a).*

these zones are determined by specific attributes of streams, wetlands, or lakes, and sometimes by the characteristics of the adjacent terrestrial ecosystem. Constraints to forest practices are imposed within the management zone.

A riparian classification system was established in FPC regulations for streams, wetlands, and lakes, and is continued under the FRPA (see Forest Planning and Practices Regulation). In this system, streams are classified from S1 to S6 based on:

- fish presence,
- location in a community watershed, and
- average channel width.

Stream classification is based on the "reach" concept. A reach is understood to be a relatively homogeneous length of stream having a sequence of repeating structural characteristics (or processes) that also correspond to fish habitat types. The key physical factors used to determine reaches in the field are channel pattern, channel confinement, gradient, and streambed and streambank materials. Stream reaches generally show uniformity in these characteristics and in discharge (see B.C. Ministry of Forests and B.C. Ministry of Environment 1995a). The characteristics of stream reaches are described further in the *Fish-stream Identification Guidebook* (B.C. Ministry of Forests and B.C. Ministry of Environment 1998).

Streams and reaches were defined separately in the FPC. Only the definition of stream has been retained for the FRPA, and is modified slightly to include a 100-m minimum channel length, which corresponds to the 100-m minimum reach length specified in the FPC. Under Section 1 of the Forest Planning and Practices Regulation:

> *"'stream' means a watercourse, including a watercourse that is obscured by overhanging or bridging vegetation or soil mats, that contains water on a perennial or seasonal basis, is scoured by water or contains observable deposits of mineral alluvium, and that*
> *(a) has a continuous channel bed that is 100 m or more in length, or*
> *(b) flows directly into*
> *(i) a fish-stream or a fish-bearing lake or wetland, or*
> *(ii) a licensed waterworks."*

Watercourses failing to meet this definition are not subject to the management provisions presented in Table 15.1, which summarizes the riparian classification system for streams and the width and retention standards for the associated riparian reserves and management zones. Riparian classes S1–S4 are fish-bearing streams or streams in community watersheds. Classes S5 and S6 are streams without fish.

Similarly, prescribed classifications for reserve and management zones of lakes and wetlands depend on water-body size and other characteristics (Figures 15.4 and 15.5; Tables 15.2 and 15.3). The four riparian classes of lakes (L1–L4) are determined by:

- lake size, and
- the biogeoclimatic ecosystem classification (BEC) unit in which they occur.

TABLE 15.1 *Riparian management area standards for streams under the FPC and FRPA. Widths of reserve and management zones are slope distances measured from the streambank perpendicular to the channel. This classification framework developed for the FPC has been retained under the FRPA.*

Riparian class	Average channel width (m)	Reserve zone width (m)	Management zone width (m)	Total width of RMA (m)	Retention in RMZ (%)[a]
S1-large (FPC) = S1-A (FRPA)	> 100 (for > 1 km of stream length)	0	100	100	≤ 70[b]
S1 (FPC) = S1-B (FRPA)	> 20	50	20	70	50
S2	> 5 to ≤ 20	30	20	50	50
S3	1.5 to ≤ 5	20	20	40	50
S4	< 1.5	0	30	30	25
S5[c]	> 3	0	30	30	25
S6[c]	≤ 3	0	20	20	5

a Recommended in the *Riparian Management Area Guidebook* for FPC only as maximum and averaged over large operating areas, not specific to each cutblock (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a).
b Softwood retention = 50% within 20 m of island perimeters and channel banks (see Table 6, B.C. Ministry of Forests and B.C. Ministry of Environment 1995a). Hardwood retention as per active floodplains = 70% (see Table 6, B.C. Ministry of Forests and B.C. Ministry of Environment 1995a).
c Non-fish-bearing streams.

The specified distances for the reserve zone and management zone of each lake riparian class is presented in Table 15.2. The outer edge of the lake is measured from the high-water mark or the edge of an immediately contiguous wetland.

Wetlands include shallow open water, swamps, marshes, fens, and bogs (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a). The FPC definition of wetland has been retained under FRPA as: "a wetland is a swamp, marsh, or other similar area that supports natural vegetation, that is distinct from the adjacent upland areas" (Forest Planning and Practices Regulation). The *Riparian Management Area Guidebook* (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a) further described wetlands as areas where "the water table is at, near, or above the surface or where soils are water-saturated for a sufficient length of time that excess

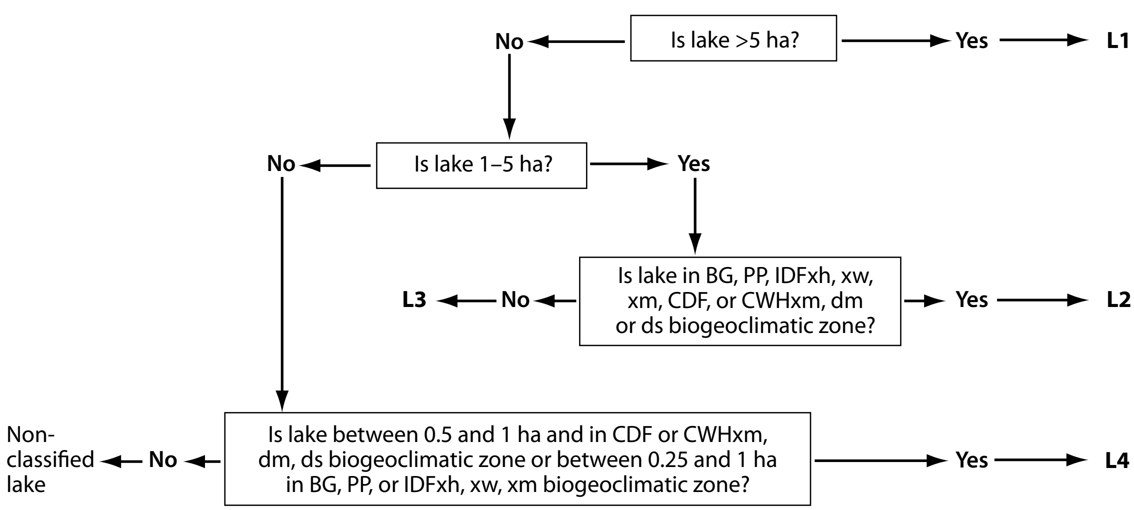

FIGURE 15.4 *Riparian classification key for lakes under the FPC and FRPA (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a). Interior BEC zones: BG = Bunchgrass, PP = Ponderosa Pine, IDF = Interior Douglas-fir. Coastal BEC zones: CDF = Coastal Douglas-fir, CWH = Coastal Western Hemlock. BEC subzones: xm = very dry (xeric), maritime; xw = very dry, warm; dm = dry, mild; ds = dry, submaritime.*

TABLE 15.2 *Riparian management area standards for lakes under the FPC and FRPA. Management zone widths for class L1 lakes of less than 1000 ha were established by the district manager (DM) under the FPC, and by the Minister or delegated decision maker (DDM) under the FRPA.*

Riparian class	Reserve zone width (m)	Management zone width (m)[a]	Total width of RMA (m)
L1 > 1000 ha (FPC) = L1-A (FRPA)	0	0	0
L1 < 1000 ha (FPC) = L1-B (FRPA)	10	Set by DM (FPC) or by Minister/DDM (FRPA)	10 (+ RMZ set by DM/DDM)
L2	10	20	30
L3	0	30	30
L4	0	30	30

a Maximum overall RMZ retention guideline under the FPC was 25% by tree basal area for all lake and wetland classes combined within an area covered by a Forest Development Plan. Limits are not given under the FRPA except for minor tenure holders (≥ 10%).

TABLE 15.3 *Riparian management area standards for wetlands under the FPC and FRPA*

Riparian class	Reserve zone width (m)	Management zone width (m)[a]	Total width of RMA (m)
W1[b]	10	40	50
W2	10	20	30
W3	0	30	30
W4	0	30	30
W5[b]	10	40	50

a Maximum overall riparian management zone retention guideline under the FPC was 25% by tree basal area for all lake and wetland classes combined within an area covered by a forest development plan. Limits are not given under the FRPA except for minor tenure holders (≥ 10%).

b Under the FPC, no riparian reserve or riparian management zone was required for upland terrain within a bog-dominated or muskeg-dominated wetland larger than 1000 ha in boreal, sub-boreal, or hypermaritime climates. However, where a reserve or management zone was established by the district manager, the RMA was recommended to reflect the landscape-level management strategy that was outlined in the *Biodiversity Guidebook* (B.C. Ministry of Forests and B.C. Ministry of Environment 1995b). Under FRPA, these considerations are specific to W1 wetlands, and the reserve and (or) management zone that may be required by the Minister or DDM are restricted in width to ≤ 10 m and ≤ 40 m, respectively (see Forest Planning and Practices Regulation).

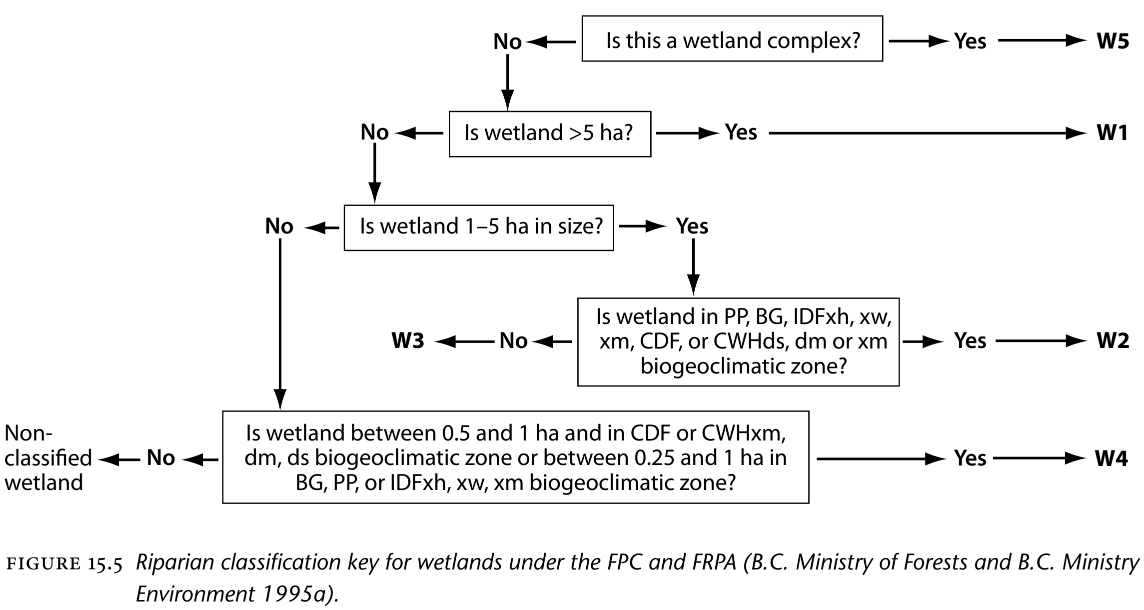

FIGURE 15.5 *Riparian classification key for wetlands under the FPC and FRPA (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a).*

water and resulting low oxygen levels are principal determinants of vegetation and soil development."

The five riparian classes of wetlands (W1-W5) are based on:

- whether the wetland is a simple wetland or a wetland complex,
- wetland size, and
- the biogeoclimatic unit in which the wetland occurs.

A wetland complex exists where the riparian management area of one wetland overlaps that of one or more other wetlands. Class W1-W4 wetlands are simple wetlands, whereas class W5 is a wetland complex.

Fisheries-sensitive and Marine-sensitive Zones or Features

Since the implementation of the FPC, two additional areas have been addressed within British Columbia's riparian management systems: (1) fisheries-sensitive zones and (2) marine-sensitive zones (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a, 1998). Fisheries-sensitive zones were defined in the FPC to include "side and back channels, ponds, swamps, seasonally flooded depressions, lake littoral zones, and estuaries that are seasonally occupied by over-wintering fish." This definition was problematic because it included a mix of stream and non-stream features. Accordingly, the definition was revised for FRPA to manage those sites occupied by fish but not covered by the definitions of stream or wetland. Under FRPA, fisheries-sensitive zones are called "fisheries-sensitive features" and include:

- the littoral zone of a lake;
- a freshwater area where the water is less than 10 m deep; and
- a flooded depression, pond, or swamp that is not a stream, wetland, or lake, but
  - either perennially or seasonally contains water, or
  - is seasonally occupied by a species of fish referred to in paragraph (a) of the definition of fish-bearing stream (Forest Planning and Practices Regulation).

Marine-sensitive zones were defined under the FPC to include herring spawning areas, shellfish beds, marsh areas, existing aquaculture sites, juvenile salmonid-rearing areas, and adult salmon–holding areas. All of these locations are retained under the current "marine-sensitive features" definition in the FRPA, with the addition of the littoral zones of marine and estuary systems and marine areas where water is less than 10 m deep. For further information on the classification of riparian management areas for streams, lakes, and wetlands, see the *Riparian Management Area Guidebook* (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a), the *Fish-stream Identification Guidebook* (B.C. Ministry of Forests and B.C. Ministry of Environment 1998), and the FRPA Forest Planning and Practices Regulation.

Achieving Riparian Management Area Objectives

In British Columbia, riparian management area objectives were achieved under the FPC with a mixture of prescriptive standards (e.g., streamside reserves with specified minimum widths) and planning and practices requirements under the Operational Planning Regulation and Timber Harvesting Regulation, as well as non-prescriptive guidance. The *Riparian Management Area Guidebook* (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a) identified considerations for practices around the different riparian classes of streams. Where a stream had both an inner reserve zone and outer management zone (fish-bearing classes S1–S3), the guidebook recommended practices that:

- reduced the risk of windthrow into the reserve zone (Figure 15.6); and
- retained important wildlife habitat attributes including wildlife trees, large trees, hiding and resting cover, nesting sites, structural diversity, coarse woody debris, and food sources characteristic of natural riparian ecosystems.

Where a riparian management area had only a management zone (e.g., fish-bearing class S4 streams; non-fish-bearing classes S5 and S6 streams), practices were recommended to:

- retain sufficient vegetation along streams to provide shade (Figure 15.7), reduce bank microclimate changes, maintain natural channel and bank stability and, where specified, maintain important attributes for wildlife; and

FIGURE 15.6 *Riparian management area windthrow on small stream. (Photo: R.G. Pike)*

FIGURE 15.7 *Provision of shade. (Photo: R.G. Pike)*

- retain key wildlife habitat attributes adjacent to wetlands and lakes that were characteristic of natural riparian ecosystems.

A set of recommended "best management practices" was provided for the management zones of streams, wetlands, and lakes to help meet riparian objectives (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a); however, a wide range of acceptable practices was possible for any site depending on factors such as windthrow hazard (Chatwin et al. 2001). This generated considerable debate around the adequacy of best management practices for water bodies protected solely with riparian management zones—that is, for small fish-bearing streams (class S4) and those streams without fish (class S6) as well as the larger, non-fish-bearing streams (class S5) (Chatwin et al. 2001).

One reason for supplanting the prescriptive FPC with the results-based FRPA was to increase management efficiency by allowing forest licensees more latitude to identify and implement practices on the ground that are best suited to specific conditions. Within the legal framework of the FRPA, licensees are provided with the ability and responsibility to manage within a regime based on professional reliance and accountability (see subsection, "Site- and Watershed-level Approaches under the *Forest and Range Practices Act*," below). The expected environmental outcomes or "results" of management practices remain essentially the same between the FPC and FRPA. Within the FPC, the methods to achieve government objectives were largely prescribed, except that more flexibility was permitted within the riparian management areas of smaller streams (classes S4–S6). This prescriptive regime also required government review and approval of all forestry plans, from 5-year forest development plans, which covered relatively large operating areas, to site-level harvest plans. Furthermore, any amendments during the life of the plans had to be reviewed and approved by government. The cost and administrative encumbrances of this system were other reasons to establish a results-based system in which the only step involving government review and approval is at the initial forest stewardship plan stage (replacing the forest development plan) when licensees identify the strategies and (or) results that will ensure that their operations are consistent with government's stated objectives in the FPPR to: "conserve water quality, fish habitat, wildlife habitat and biodiversity in those riparian areas" (Forest Planning and Practices Regulation). More details on the contrasts between FRPA and FPC are provided in the next section.

RIPARIAN MANAGEMENT SYSTEMS IN BRITISH COLUMBIA

Since 1995, three riparian management schemes have emerged for wide application in British Columbia. Two of these schemes are the legislated management systems under the *Forest Practices Code of British Columbia Act* and its successor, the current *Forest and Range Practices Act*. The third scheme was developed by the Forest Stewardship Council of Canada, a non-government body that offers environmental certification for land-use practices. All of these schemes are generally based on the water-body classification system developed for the FPC.

The prescriptive FPC and the results-based FRPA differ primarily in that FRPA provides more explicit latitude to vary riparian management standards from legislated defaults. Departure from default standards would be based on site-level and watershed-level characteristics. The Forest Stewardship Council system is generally a more conservative approach that requires higher levels of riparian retention for all water-body classes, in particular for small streams (classes S4–S6). This system is voluntary, and can be one of the alternative approaches approved by government under a FRPA forest stewardship plan.

In British Columbia, small streams included within the S4–S6 categories have been the focus of attention and debate because these streams are particularly challenging to manage. Within each class, these streams exhibit a diverse array of channel sizes, channel types, drainage-system linkages, and ecological functions. Collectively, S4–S6 streams may make up 80% or more of the total length of the drainage network within a given watershed. Because of this abundance and diversity, riparian management strategies for small streams ideally need to be flexible, adaptable, and tailored to the operating area and specific environments.

A "landscape-level" approach has also received some conceptual attention in British Columbia in recent years. In this section, we summarize all of these approaches and concepts.

Forest Practices Code Approach to Riparian Management

In various forms, the site-level, rules-based approach for riparian management is common to all jurisdictions in northwestern North America. These schemes are the easiest to implement and administer and have been presumed to provide consistent and reasonable levels of protection for aquatic resources, although few jurisdictions have implemented systematic and widespread post-harvest effectiveness assessments (see "Riparian Assessments in British Columbia," below). The FPC's prescriptive approach, based on riparian classification, legislatively specified the minimum widths for riparian management areas and the associated reserve and management zones. For streams, these widths varied on the basis of channel width, stream gradient, community watershed use, and fish presence. These limited attributes were meant to identify appropriate levels of vegetation retention and management activities that minimized the introduction of sediment (especially fine sediments) and woody debris into water bodies, which included a wide array of stream types within many different environmental settings. The intention was to provide protection for a broad range of riparian values, including wildlife, biodiversity, channel and aquatic habitat integrity, and water quality.

In reality, the FPC approach for riparian management was a mixture of rules and results-based elements. The rules-based system of riparian reserves and management zones of prescribed minimum widths was established as a surrogate for desired riparian management outcomes (results) because the exact thresholds for riparian, channel, and aquatic ecosystem responses to streamside management activity, site disturbance, and vegetation retention were (and remain) unknown. Rules were also contained within practices regulations (e.g., Timber Harvesting Practices Regulation) to govern activities in riparian management zones. The objective was to maintain the integrity of the reserves, and for those streams where no reserves were prescribed, to maintain the integrity of channels and aquatic habitats (e.g., machine-free zones within 5 m of the channel bank).

For water bodies without mandatory riparian reserves, the FPC scheme embodied more of a results-based approach. Forest licensees were permitted wide latitude around riparian retention and management practices to achieve riparian management objectives within the zone (e.g., Table 15.1). Streams managed by these criteria included the smallest inhabited by fish (class S4 streams less than 1.5 m wide), and those without fish (classes S5 and S6). The riparian management area around class S4–S6 streams consisted solely of a management zone in which forestry practices were guided by objectives listed within the *Riparian Management Area Guidebook*, including recommendations for best management practices (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a).

The widths of riparian reserve and management zones under the FPC were established so that streams, lakes, and wetlands of different types and sizes would receive sufficient protection to preserve key functions during and after forestry operations. However, the FPC riparian standards also reflected an attempt to balance riparian tree retention for environmental protection with the economic and social values around access to timber. To manage the impact on timber supply, mandatory no-harvest riparian reserves were provided for streams containing the highest aquatic resource values (i.e., fish-bearing streams greater than 1.5 m but less than 100 m wide) and included within riparian classes S1–S3. One management trade-off with this decision was that no legally mandatory riparian reserves were required for the smallest fish-bearing streams, streams without fish, or large rivers. This also allowed for site-specific flexibility in managing the highly diverse population of small streams. Rivers with reaches more than 100 m wide for more than 1 km were not provided with mandatory reserves because riparian areas have minimal influence on the ecological and hydrological functions of very large watercourses.

The two most commonly voiced criticisms of the FPC's forest management approach focussed on:

1. the use of timber supply impact considerations in establishing the standards for environmental protection, including riparian reserves and the recommended levels of tree retention in riparian management zones; and
2. the lack of mandatory riparian reserves for small fish-bearing streams and the directly associated non-fish-bearing tributaries.

Critics generally advocated more conservative and risk-adverse approaches such as mandatory riparian reserves for class S4 and S6 streams. In response to similar criticisms in the late 1990s, other jurisdictions such as Washington State amended forest practice rules to provide greater protection to these small streams.

The FPC riparian management regime was based on a strategy of acceptable risk and had the goal of achieving effective levels of riparian protection while also allowing for some timber-harvesting opportunities. An area-based analysis[1] of potential impacts on timber harvesting opportunities suggests that riparian reserves and best management practices for tree retention in riparian management zones under the FPC would have reduced the area available for timber harvest by about 11% in coastal British Columbia, by more than 2% in the Interior, and by more than 6% overall (see retention targets in Table 15.1). Using the same analysis method, and to illustrate the factors FPC developers considered in the mid-1990s, estimates from maps of stream channel networks show that implementing no-harvest riparian reserves 30 m wide on all S4 and S5 streams, and 20 m wide on all S6 streams—with no management flexibility regardless of the circumstances—would reduce the amount of land available for harvest by 22% in coastal British Columbia, by nearly 6% in the Interior, and by nearly 14% overall.

Notwithstanding the criticisms of the FPC riparian management standards or any shortcomings of its prescriptive approach, the Forest Practices Board (1998) concluded from its evaluation of FPC and licensee performance in coastal areas that the FPC had significantly improved the protection and maintenance of riparian and stream values over pre-FPC conditions, particularly for the larger fish-bearing streams that received no-harvest riparian reserves. Any problems detected were associated mainly with missed and incorrectly classified small streams, and changes were made to improve stream identification and classification outcomes. In 2000, an interagency survey of classified S4 streams on the central Interior plateau (former Kamloops and Cariboo Forest Regions) concluded that these streams were managed to FPC standards (Chatwin et al. 2001) and were generally meeting the objectives laid out in the *Riparian Management Area Guidebook* (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a). Overall, the study observed a low degree of short-term impacts to stream channels; however, these results were achieved in management regimes where the overall level of riparian tree retention (49%) was substantially higher than the maximum level (25% by basal area) recommended in the guidebook. Full-retention (30 m wide) reserves or similar high-retention riparian treatments were common (Chatwin et al. 2001; Figure 15.8).

FIGURE 15.8 *Smaller stream with full riparian area management retention. (Photo: R.G. Pike)*

1 Wildstone Resources. 1996. Riparian impact assessment. Unpubl. report.

The same central Interior study looked at whether common management practices were adversely affecting S4 streams. Questions were immediately raised about whether the management strategies and outcomes in the central Interior were typical of the rest of the province. Under the British Columbia Forest and Range Evaluation Program (FREP), assessments have focussed on addressing this question and others related to the effectiveness of regulations and practices in maintaining forest values including water, fish, biodiversity, and soils (for more details, see www.for.gov.bc.ca/hfp/frep/). Results from province-wide field assessments between 2005 and 2008 (1441 streams managed under the FPC) revealed that about 11% of S4 streams and 19% of S6 streams were not in properly functioning condition because of various factors including roads, road crossings, and low levels of riparian retention (for more details, see "Riparian Assessments in British Columbia" below).

Site- and Watershed-level Approaches under the *Forest and Range Practices Act*

Results-based approaches are designed to provide for increased management flexibility, and are informed by existing watershed-scale information and (or) new data from integrated riparian assessments. By taking into account linkages between low-order headwater streams and high-order, valley-bottom channels, the goal is to implement riparian management on a more ecologically efficient and relevant basis than is possible when using rigid prescriptive regimes. Under the current FRPA, two options are available for riparian management:

1. the default prescriptive approach that mirrors the FPC (see "Forest Practices Code Approach to Riparian Management" above), and
2. an alternative approach set out in a forest stewardship plan, approved by government, which contains the results or strategies that show that a forest licensee is being consistent with government's objectives for riparian areas.

The first option is similar to the FPC approach in that it retains all FPC riparian classification systems for water bodies and a mixture of rules-based/results-based elements around riparian management zones. Tree retention requirements by basal area for these zones are not specified in regulation except for minor tenure holders (Table 15.4). The *Riparian Management Area Guidebook* (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a) is available for guidance regarding best management practices for retention in riparian management areas; however, this guidebook has no legal status under the current FRPA.

The second option provides freedom to manage. A proponent who wishes to vary from the prescriptive defaults must include results or strategies in a forest stewardship plan to address the objective set by government for water, fish, wildlife, and biodiversity within riparian areas, which is: "without unduly reducing the supply of timber from British Columbia's forests, to conserve, at the landscape level, the water quality, fish habitat, wildlife habitat and biodiversity associated with those riparian areas" (Forest Planning and Practices Regulation). Specifically, the plan must contain a result or strategy that addresses retention of trees in a riparian management area (Forest Planning and Practices Regulation). By giving licensees the option to implement the default prescriptive approach with fixed riparian reserve and management zones, the Act accommodates licensees who do not have the necessary expertise or resources to undertake and implement strategies for alternative riparian management schemes (e.g., complete assessments in support of these strategies), or who are otherwise unwilling to assume the costs and responsibilities of the results-based regime.

Regardless of the riparian management option chosen, other considerations may apply. For example, licensees may need to provide results or strategies to meet the requirements for government-designated, fisheries-sensitive watersheds where the intent is to prevent "the cumulative hydrological

TABLE 15.4 *Riparian management zone tree retention requirements by percent basal area for minor tenure holders under the* Forest and Range Practices Act *(Forest Planning and Practices Regulation)*

Riparian class	Percent basal area to be retained within RMZ
S1 (A and B) streams	≥ 20
S2 streams	≥ 20
S3 streams	≥ 20
S4 streams	≥ 10
S5 streams	≥ 10
S6 streams	Not applicable
All classes of wetlands and lakes	≥ 10

effects of primary forest activities in the fisheries sensitive watershed from resulting in a material adverse impact on the habitat of the fish species for which the fisheries sensitive watershed was established" (Forest Planning and Practices Regulation). Similarly, licensees are required to meet the objectives for water quality in community watersheds, and must not conduct activities in coastal areas that would cause the destabilization of alluvial fans (Forest Planning and Practices Regulation).

No guidance is explicitly provided within the Act to assist licensees with alternative riparian management approaches. The vision of this regime is that these approaches are proponent-implemented, inventory-based, and flexible. Plans and practices would be informed by existing knowledge for an area and (or) information collected at a watershed level that optimally would include the results of integrated riparian assessments. The intent is for alternative riparian retention schemes to be rationally informed from relevant knowledge, which integrates hillslope-stream channel linkages with stand-level requirements for riparian function. This information or process does not necessarily appear in a forest stewardship plan, but forms part of a licensee's non-legal background information as the rationale for the plan.

The Act depends extensively on "professional reliance" to deliver expected management outcomes. Generally, a team of qualified specialists on behalf of the proponent conducts planning and pre-harvest assessments. This team may consist of a geomorphologist and (or) hydrologist, forester, wildlife biologist, and fish-habitat biologist. The widths of riparian management areas and reserve zones are intended to be flexible to maintain riparian function, rather than be based on any arbitrary, fixed, and predetermined minima. Logically, this flexible approach is not necessarily anchored to stream classes, but rather to the riparian stand requirements of the stream, sediment and LWD transport potential, and hillslope-channel connections (i.e., to suit local watershed characteristics). When alternative riparian management approaches are implemented in this way, they are consistent with the current riparian management schemes associated with environmental certification (e.g., Forest Stewardship Council of Canada).

Post-harvest effectiveness evaluations are also a part of the FRPA management structure. Forest licensees may implement their own monitoring initiatives; however, the provincial government will monitor the effectiveness of its legislation, regulations, and licensee-implemented management practices province-wide for the purposes of adaptive management and continuous improvement.

A comprehensive watershed-based approach has the following advantages.

- Riparian protection is delivered on a more ecologically sound basis: retention (e.g., riparian reserves) is applied when and where it will provide maximum ecological benefits.
- A licensee-driven system of planning and implementation is within an adaptive management, results-based framework.
- Consistency is achieved with schemes currently proposed by environmental certification initiatives (e.g., the Forest Stewardship Council).

Forest Stewardship Council

The Forest Stewardship Council's main riparian standards for British Columbia reflect a more conservative management approach by using both riparian reserves and high-retention riparian management zones (Table 15.5). This scheme is somewhat similar to FRPA because it permits a prescriptive-like option with fixed-width reserve and management zones and an assessment-based, variable-width alternative. In addition, both management models incorporate the principles of post-harvest effectiveness monitoring within an adaptive management framework; however, the Council's alternative scheme is explicitly based on the requirement to conduct comprehensive riparian assessments and apply a minimum riparian retention budget as a part of the planning process at the watershed level or for other landscape-level ecological units of 5,000–50,000 ha.

The Council's riparian standards are generally based on the FPC/FRPA riparian classification framework. Therefore, direct comparisons to the FPC and default FRPA standards are possible if the Council's mandatory riparian retention budget is achieved with fixed-width reserve and management zones (Tables 15.5, 15.6, and 15.7). Such comparisons reveal substantial differences. For example, the Council subdivides class S5 and S6 non-fish-bearing streams to provide additional reserve-zone protection (20 m wide) for community watersheds, and for fish habitat that might be affected by operations occurring around the direct tributaries to fish-bearing streams (classes S5a and S6a).

By comparison, the Council's standards also provide:

TABLE 15.5 *Comparison of Forest Stewardship Council (FSC) riparian standards for streams with those of the FPC and FRPA*

Riparian class		Average channel width (m)		Reserve zone width (m)		Management zone width (m)		Total RMA width (m)		RMZ retention (%)	
FSC	FPC/FRPA	FSC	FPC/FRPA	FSC	FPC/FRPA	FSC	FPC/FRPA	FSC	FPC/FRPA	FSC	FPC only
S1a	S1 large/S1-A	> 100	≥ 100	30	0	40	100	70	100	65	≤ 70
S1b	S1 / S1-B	> 20	> 20	30	50	40	20	70	70	65	50
S2	S2	> 5 to ≤ 20	> 5 to ≤ 20	30	30	40	20	70	50	65	50
S3	S3	1.5 to ≤ 5	1.5 to ≤ 5	30	20	20	20	50	40	65	50
S4	S4	< 1.5	< 1.5	30	0	20	30	50	30	65	25
S5a[a]	S5	> 3	> 3	20	0	20	30	40	30	65	25
S5b[b]	S5	> 3	> 3	0	0	15	30	15	30	30/10	25
S6a[c]	S6	0.5 to 3	≤ 3	20	0	20	20	40	20	65	5
S6b[d]	S6	≤ 3	≤ 3	0	0	15	20	15	20	30/10	5

a S5a: No fish, not in a community watershed, >3 m wide, and (1) in a domestic watershed, and (or) (2) ≤ 500 m upstream from a fish-bearing stream, and (or) (3) >10 m wide.
b S5b: No fish, not in a community watershed, 3–10 m wide, not in a domestic watershed, and > 500 m upstream from a fish-bearing stream. RMZ retention is 30% except in Natural Disturbance Type 3 (NDT3 ecosystems with frequent stand-initiating events) where it is 10%.
c S6a: No fish, not in a community watershed, 0.5–3 m wide in the interior region (1–3 m in the coast) and (1) in a domestic watershed, and (or) (2) ≤ 250 m upstream from a fish-bearing stream.
d S6b: No fish, not in a community watershed, and (1) 0.5–3 m wide and not in a domestic watershed, and > 250 m upstream from a fish-bearing stream, or (2) < 0.5 m wide in the interior region (<1 m in the coast). RMZ retention is 30% except in NDT3 where it is 10%.

TABLE 15.6 *Comparison of Forest Stewardship Council (FSC) riparian standards for wetlands with those of the FPC and FRPA*

Riparian class		Wetland size (ha)		Reserve zone width (m)		Management zone width (m)		Total RMA width (m)		Retention in RMZ (%)	
FSC	FPC/FRPA	FSC	FPC/FRPA	FSC	FPC/FRPA	FSC	FPC/FRPA	FSC	FPC/FRPA	FSC	FPC only[a]
W1	W1	> 5 to < 1000	> 5 to < 1000	20	10	15	40	35	50	30	25
W2[b]	W2	1 to 5	1 to 5	20	10	15	20	35	30	30	25
W3[b]	W3	1 to 5	1 to 5	20	0	15	30	35	30	30	25
W4[c]	W4	0.25/0.5 to 1	0.25/0.5 to 1	20	0	15	30	35	30	30	25
W5	W5	< 1000	< 1000	20	10	15	40	35	50	30	25
UNC_{fish}	UNC	< W4 minima	< W4 minima	20	0	15	0[e]	35	0	30	0
UNC[d]	UNC	< W4 minima	< W4 minima	0	0	15	0[e]	15	0	30	0

a Recommended maximum and averaged among cutblocks.
b Class W2 and W3 wetlands are distinguished by location in different biogeoclimatic zones.
c Minimum size of Class W4 wetlands depends on biogeoclimatic zone.
d UNC_{fish} = unclassified wetland with fish. UNC = unclassified wetland without fish.
e Machine-free zone 5 m wide usually implemented for FPC.

- reserves for more streams including 30 m wide riparian reserve zones for all fish-bearing classes including S4 streams and S1a large rivers;
- wider reserves, and more classes requiring reserves, for both wetlands and lakes;
- reserves that are narrower than or equal in width to FPC/FRPA stream classes S1 and S2, but have tree retention by basal area increased to 65% in riparian management zones;
- 65% tree retention levels by basal area in the riparian management zones of all streams except classes S5b and S6b; 30% retention in the management zones of all lakes and wetlands;
- wider riparian management zones for some

TABLE 15.7 *Comparison of Forest Stewardship Council (FSC) riparian standards for lakes with those of the FPC and FRPA*

Riparian class		Lake size (ha)		Reserve zone width (m)		Management zone width (m)		Total RMA width (m)		Retention in RMZ (%)	
FSC	**FPC/ FRPA**	**FSC**	**FPC/ FRPA**	**FSC**	**FPC/ FRPA**	**FSC**	**FPC/ FRPA**	**FSC**	**FPC/ FRPA**	**FSC**	**FPC only**[a]
L1	L1/L1-B	> 5	> 5 to 1000	15	10	15	0[b]	30	10	30	25
L1	L1 large/L1-A	> 5	> 1000	15	0	15	0[b]	30	0	30	25
L2[c]	L2	1 to 5	1 to 5[c]	15	10	15	20	30	30	30	25
L3[c]	L3	1 to 5	1 to 5[c]	15	0	15	30	30	30	30	25
L4[d]	L4	0.25/0.5 to 1	0.25/0.5 to 1[d]	15	0	15	30	30	30	30	25
UNC$_{fish}$	UNC	< L4 minima	< L4 minima[e]	15	0	15	0	30	0	30	0
UNC[e]	UNC	< L4 minima	< L4 minima[e]	0	N/A	15	N/A	15	N/A	30	N/A

a Recommended maximum and averaged among cutblocks.
b L1 lakes have an additional lakeshore management zone established by the district manager. In the FPC, this was summarized within a regional lakeshore management guidebook, where these were available.
c Class L2 and L3 lakes are distinguished by location in different biogeoclimatic zones.
d Minimum size of Class L4 lakes depends on biogeoclimatic zone.
e UNC$_{fish}$ = unclassified lake with fish. UNC = unclassified lakes without fish.

streams including S1b (FRPA S1-B), S2, and S5a (FRPA S56): where management zones are narrower for fish-bearing streams, basal area retention is higher;

- narrower or equal-width management zones for non-fish-bearing streams but with basal area retention increased to 65% when they are in domestic watersheds or within specific distances from fish-bearing streams.

The Forest Stewardship Council riparian management approach represents a relatively low management-related risk to streams, lakes, wetlands, and the associated biota. The overall approach recognizes the broad principles of aquatic-riparian processes and riparian function and, for streams, addresses drainage network linkages by providing an elevated level of management attention to small headwater streams with sufficient hydraulic power to influence other parts of the drainage.

The Council's assessment-based management alternative allocates riparian tree retention on the basis of comprehensive, e.g., watershed-level, assessments that must integrate hillslope-stream channel linkages with stand-level requirements for hydroriparian function and wildlife values. However, the scope of management freedom faces some limitations because of the need to retain a minimum proportion of the total riparian area in an unharvested state (≥ 80% in reserves) within a defined operating area (a minimum-budget approach; Table 15.8).

In spite of implementation costs and other considerations, the assessment-based approach of the Forest Stewardship Council is conceivably one that a licensee might wish to propose under FRPA as an alternative to prescriptive defaults. However, regardless of whether this approach uses minimum-retention budgets or not, a full freedom-to-manage scheme has significant challenges. A watershed-based, flexible approach with integrated aquatic and terrestrial ecosystem requirements has not yet been implemented broadly in any jurisdiction, probably because of its inherent complexity, the need for extensive inventory data and technical expertise, and the costs associated with inventories, planning, and post-harvest monitoring.

A watershed-based, flexible approach is also more difficult to apply than default standards, and potentially prone to subjectivity in ranking different riparian values. Different riparian ecotypes have yet to be identified and defined for most parts of British Columbia. The appropriate level of riparian retention for such ecotypes remains a challenging choice although post-harvest effectiveness evaluations can contribute to learning and management adaptation.

Compliance and enforcement may also be more difficult to administer, and results (e.g., water temperature, suspended sediment, channel stability, etc.) may be difficult to audit and interpret in terms of the natural range of variability (see "Riparian Assessment in British Columbia" below). Co-ordinating activities with multiple licensees or tenures within a watershed area can also present challenges under this system.

TABLE 15.8 *Minimum budgets to be applied for the Forest Stewardship Council's (FSC) assessment-based riparian management option for streams (per length of stream channel) and by average equivalent riparian reserve and management zone widths*

		Minimum reserve zone budget		Minimum management zone budget		
FSC riparian (stream) class	**Application**	**By area (ha/km)**	**Reserve zone equivalent width (m)**	**By area (ha/km)**	**Management zone equivalent width (m)**	**RMZ basal area retention (%)**
S1a, S1b, S2	Streams with fish or in a community watershed and > 5 m wide	6	30	8	40	65
S3, S4	Streams with fish or in a community watershed and < 5 m wide	6	30	4	20	65
S5a, S6a	Without fish, not in a community watershed: **(1)** >3m wide and (a) in a domestic watershed, and(or) (b) ≤ 500 m upstream from a fish-bearing stream, and(or) (c) >10 m wide; **or** **(2)** 0.5–3 m wide in the interior region, 1–3 m wide in the coast region, and (a) in a domestic watershed and(or) (b) ≤ 250 m upstream of a fish-bearing stream	4	20	4	20	65
S5b, S6b	Without fish, not in a community watershed: **(1)** >3 to 10 m wide, not in a domestic watershed, and >500 m upstream of a fish-bearing stream, **or** **(2)** 0.5–3 m wide, not in a domestic watershed, and >250 m upstream of a fish-bearing stream **or** **(3)** <0.5 m wide in the interior region, <1 m wide in the coast region	0	0	3	15	30 (10 in NDT3)

Landscape-level Riparian Management Approaches

Riparian management approaches that are solely site-based do not address landscape-level issues and cumulative effects. The effectiveness of a particular riparian management area prescription may be strongly influenced by what is happening elsewhere in the landscape (e.g., landslides from upper watershed areas).

Landscape-level approaches for riparian management allow:

- a shift from the rigid buffer-width strategy to a more flexible one that is based on the characteristics of the stream and the historic array of disturbance conditions at the landscape level;
- the ability to achieve water temperature, suspended sediment, and LWD objectives by controlling the proportion of the landscape in various forested conditions; and
- greater flexibility in scheduling the extent and frequency of harvesting; that is, disturbances caused by harvesting can be concentrated in different sub-basins, which then are provided with long periods for watershed recovery.

Implicit within the landscape approach are results that include:

- mainstream channels with variable-width riparian reserves based on channel type and floodplain width;
- portions of the landscape having small streams, which are capable of transporting debris, protected by either reserves or high-retention management zones;
- portions of the landscape with no reserves and (or) minimal tree retention for small streams;
- an overall riparian forest condition more similar to pre-harvest levels than the most common current post-harvest outcome, which leaves relatively low levels of retention for small streams and, for larger ones, a network of older-age riparian strips within a landscape dominated by young, regenerating stands; and
- a retained riparian forest that can serve aquatic

protection objectives and integrate biodiversity objectives.

A hypothetical example of a landscape approach is given in Table 15.9. Alternative models can be contemplated, such as those focussed at more local scales and based on channel guilds identified on the basis of terrain, morphological type (including incised vs. unconstrained), sensitivity to disturbance, hillslope-channel connectivity, and channel-to-channel connectivity.

Landscape approaches are challenging to implement, not only technically but also socially. For example, an analysis of disturbance regimes and channel sensitivity may result in some streams actually receiving less protection from reserves or management zones than these streams presently do. These outcomes are potentially unpopular with the public, fisheries resource managers, and others concerned with fish stocks and other species already at risk because of various causes. For example, the Blue River Management Plan in Oregon originally envisioned a full landscape approach; however, the plan was ultimately modified to incorporate riparian reserves around all streams and other features because of concerns that the public would reject the plan (see Cissel et al. 1999). Landscape approaches remain problematic and may be best suited for implementation under a results-based pilot linked to a monitoring and evaluation program based on adaptive management principles. Despite the current challenges, landscape approaches linked to principles of ecosystem-based management are under development for parts of coastal British Columbia (see "Other Riparian Management Approaches," below).

Other Riparian Management Approaches

Since the late 1990s, other riparian management approaches in the Pacific Northwest have emerged in addition to those management regimes enacted by government legislation and implemented throughout a given jurisdiction. The management plan for the Plum Tree Timber Commitments in Washington, Idaho, and Montana employs a channel guild concept that groups streams within watersheds for specific management attention, identifies "channel-migration zones" as important features to buffer, and recognizes headwater streams and riparian-upland interfaces as key management factors. These elements are considered to augment existing state riparian standards to provide additional "riparian habitat area" protection for several resource values, but particularly for bull trout (*Salvelinus confluentus*) and other fish species as part of a native-fish habitat-conservation plan.

For streams with bull trout, riparian management is specifically targeted to maintain pre-harvest levels of stream shade to maintain water temperatures, and ensure an adequate LWD supply for the creation of fish habitat (Plum Tree Timber Company 1999a, 1999b). Depending on local circumstances, including sensitivity to disturbance, valley-bottom streams and wetlands may be bordered with no-harvest buffers 91 m wide. Fish-bearing streams may be provided with a 30 m wide riparian habitat area, which contains a 10-m no-harvest streamside buffer. Perennial, non-fish-bearing streams may receive a riparian habitat area 15 m wide, which contains a 9-m machine-free zone. Other areas are designated for "riparian leave trees," where trees are retained at a minimum density of 44 trees per acre (109 trees per hectare). Where streams have channel-migration zones deemed to be highly sensitive to disturbance, the entire width of the zone is restricted from harvesting. Harvest opportunities are permitted in less sensitive channel migration zones.

The concept of ecosystem-based management has emerged in recent years and in British Columbia has reached its most advanced state of development in the central and north coastal areas and on Haida Gwaii (the Queen Charlotte Islands) (Cortex Consultants 1995; Coast Information Team 2004). Key concepts within ecosystem-based management include planning and assessing at various scales from the landscape to the site, and considering the drainage network as a "hydroriparian ecosystem" with complex vertical and lateral linkages within watersheds. Within this system, the stream network is partitioned into three major zones according to dominant fluvial geomorphic processes: (1) a headwater "source zone," (2) an intermediate "transportation zone," and (3) a lower-elevation sediment "deposition zone."

The planning process for riparian management is based on comprehensive assessments and focussed on protecting hydroriparian functions and the full spectrum of aquatic and terrestrial ecosystem attributes and resource values. The *Hydroriparian Planning Guide* (Coast Information Team 2004) outlines the different steps in the planning process, which are to:

TABLE 15.9 *Hypothetical example of a landscape-level approach for riparian management based on a landscape unit of 4000 ha*

Landscape unit	Historic landscape disturbance pattern	Landscape unit objectives	Prescriptions		
			Riparian	Roads	Restoration
1	Frequent fire disturbance Frequently burned small streams No mass wasting	Even-aged management Temperature-sensitive streams	10- to 20-m reserves on streams for thermal management	Normal	Not high priority for hillslopes or streams
2	Frequent fire disturbance; north aspect Frequently burned small streams No mass wasting	Even-aged management: 70-year rotation No temperature-sensitive streams	No reserves on streams	Normal	Riparian restoration for shading No road deactivation
3	No fire disturbance High mass wasting Rain-on-snow zone	Retain large wood on unstable sites Low Equivalent Clearcut Area Reserves on all streams	Equivalent Clearcut Area limits below 25% 20- to 30-m reserves (based on stream size) on all streams	No harvest or roads on class IV and V slopes	Deactivation of high-risk roads
4	Avulsing floodplains and canyons Low fire disturbance	Retain large trees in floodplains	Variable 20- to 150-m reserves based on stream channel type and floodplain width	No roads on floodplains	In-stream LWD restoration Riparian restoration for large trees

- identify hydroriparian ecosystem functions at several scales from landscape to site;
- identify indicators for hydroriparian functions at each scale;
- provide guidance for assessing hydroriparian ecosystems in specific locations;
- define risk to hydroriparian functions that may result from forest management activities;
- identify levels of risk for ecosystem-based management at each scale;
- provide a range of management approaches and prescriptions consistent with risk so that managers can implement decisions at different scales to maintain hydroriparian ecosystems; and
- provide a framework for adaptive management and monitoring.

The management approach and objectives are conservative in this planning guide. Protecting riparian biodiversity is included and integrated with protecting biodiversity at the watershed level. To this end, broad "hydroriparian zones" are delineated as the area extending from a given water body to the edge of the influence of water on land, which is defined by the local plant community (including high-bench or dry floodplain communities) and (or) landform (e.g., gullies) plus 1.5 site-specific tree heights (horizontal distance) beyond. If landform and plant communities delineate different areas, the feature extending farthest from water is adopted as the limit of the hydroriparian zone. In the transportation and deposition hydroriparian "process" zones, the entire valley flat, plus 1.5 tree heights, is considered the hydroriparian zone. These distances were chosen because some physical functions within the hydroriparian ecosystem were estimated to be influenced to some extent within at least 1 tree height (Young 2001), and biological functions at much greater distances (Price and McLennan 2002).

Under ecosystem-based management, riparian management within the hydroriparian ecosystem of a watershed is envisioned to include default linear reserves 1.5 site-potential tree heights around all streams (regardless of size) within the transportation and deposition process zones. Patches of reserves would be established in the headwater source zone around unstable terrain (Class IV and Class V; B.C. Ministry of Forests 1999) and around concentrations of small streams. Linear reserves in the source zone may also be established where streams are deemed susceptible to debris flows or contain distinctive habitats. Similar reserves are to be applied around all wetlands and broader areas designated as "active fluvial units."

A hypothetical hydroriparian ecosystem network might also include, for example, reserves around an endangered floodplain community, 50% retention on stable alluvial fans, and patch reserves for unique and (or) representative small, steep streams to maintain connectivity. The *Hydroriparian Planning Guide* also expects managers to define and identify high-value fish habitats in the future, and requires levels of riparian protection beyond that normally applied under ecosystem-based management.

Within a given watershed, some reserved areas are envisioned to remain as reserves in perpetuity (e.g., an area of high natural instability), whereas others may become available for harvest in the long term when recovery is well advanced in contemporary harvest areas (e.g., source zone patches for preservation of representative forest). It is expected that decisions about the permanence of reserves will be made in developing an ecosystem-based regional plan that will consider its component landscapes and watersheds.

Comparison of British Columbia's Riparian Management Standards with Other Jurisdictions

Freshwater classification and management systems vary greatly among jurisdictions in northwestern North America, making direct comparison with British Columbia's riparian standards difficult. Many systems do not account for stream size, and are based primarily on fish and domestic water use. Others use stream size based on discharge, not on channel width. In several jurisdictions, all fish-bearing streams, regardless of size, are managed by the same riparian prescription for tree retention (see Tables 15.10, and 15.11).

Regardless of differences in management systems and objectives, the fixed-width riparian reserves adjacent to larger-sized fish-bearing streams in British Columbia (FRPA classes S1-B, S2, and many S3s) are wider than those of any other jurisdiction in the Pacific Northwest, except for federally managed forest lands (e.g., U.S. Department of Agriculture Forest Service Region 6) where these reserves exceed 91 m wide for fish-bearing streams of any width (Blinn and Kilgore 2001a, 2001b; Cashore 2001). On the other hand, for the majority of smaller-sized streams (i.e., classes S4–S6), all jurisdictions from Alaska to California require higher levels of riparian retention than British Columbia (Tables 15.10, and 15.11).

In general, state riparian tree retention requirements in the United States tend to be highest in the northwest, intermediate in other northern states, and the least prescriptive or restrictive in the south. A common riparian prescription across several states for fish-bearing streams or streams used for domestic water supply is a 50 ft (15.2 m) wide management zone with requirements for 50–75% crown closure or 50–75 ft^2/acre (approximately 11.5–17 m^2/ha) basal area retention after harvesting (Blinn and Kilgore 2001a, 2001b). The riparian management zone width is sometimes increased when the adjacent hillslope gradients increase beyond 30–35% (e.g., in California and Montana). Some northwest states also use a no-harvest riparian reserve from 20 to 100 ft (6.1–30.5 m) wide in addition to a management zone for the majority of small fish-bearing streams (Blinn and Kilgore 2001a, 2001b).

The wide reserves on federally managed forest lands in the Pacific Northwest were intended to deliver full protection for stream channels and aquatic habitats in response to the *Endangered Species Act* and other legislation. The width of riparian buffers required for this purpose was estimated from analyses that examined the effectiveness of riparian processes as a function of distance from the stream bank (Forest Ecosystem Management Assessment Team 1993). The distances where 100% protection was assigned for functions such as shade, organic litter fall, root strength (bank stability), riparian LWD supply, and microclimate were estimated from limited empirical data together with professional opinion and extrapolation from studies performed in non-riparian areas. In spite of criticism around the subjectivity and other limitations of the analysis,[2] the process undoubtedly satisfied the needs for a protectionist management regime for all streams, large or small.

Since the late 1990s, there has been increased information and awareness that small streams in both valley flats and headwaters are important for various watershed processes and functions (Gomi et al. 2002; Moore and Richardson 2003; Richardson 2003). Several jurisdictions already recognize

2 CH2MHill and Western Watershed Analysts. 1999. FEMAT riparian process effectiveness curves: what is science-based and what is subjective judgement? Report prepared for the Oregon Forest Industries Council, Salem, Oregon.

TABLE 15.10 *Summary of riparian standards and management practices in northwestern United States for small streams with fish and (or) used for domestic water supply (equivalent to FPC/FRPA class S4 streams, and some class S3 streams) (reserve and management zone widths are converted from measurements in feet and usually rounded to the nearest metre)*

Jurisdiction	Riparian reserve width (m)	Management zone(s) width (m)	Management zone(s) retention	Comments
U.S. Department of Agriculture Forest Service Region 6 (Pacific Northwest)	Widest of: 1. 100-year floodplain 2. Streambank to far edge of riparian vegetation 3. 2 times stand tree height (up to 91 m)	None	N/A	Example of site-potential tree height applies to the coast forest
U.S. Department of Agriculture Forest Service Region 10 (Alaska)	1. 30.5 m wide for anadromous streams 2. Others variable width (based on professional site assessment and judgement)	None	N/A	Variances to reserves common; may harvest after a Streamcourse Protection Plan is developed
Alaska State lands	1. 30.5 m for anadromous streams 2. 30.5 m for some others	1. None for anadromous 2. Most other streams with fish: 30.5 m	Non-merchantable trees for non-anadromous streams	Alaska standards vary by region; example given for Coastal Spruce–Hemlock Region
Alaska Other public lands	1. 30.5 m for anadromous streams 2. None for other streams	1. None for anadromous 2. Non-anadromous-fish streams: 30.5 m	1. N/A 2. Non-merchantable trees for non-anadromous streams	Alaska standards vary by region; example given for Coastal Spruce–Hemlock Region
Alaska Private lands	1. 20 m for high-value (low-gradient) anadromous 2. Other anadromous: the lesser of 20 m or distance to slope break 3. None for other streams	1. None for anadromous 2. None for anadromous 3. Other streams: greater of 8 m or to limit of riparian vegetation (to maximum of 15 or 30 m depending on 12% gradient break)	Non-merchantable trees "where prudent" only for larger non-anadromous-fish streams No retention specified for non-anadromous S4 equivalents	Alaska standards vary by region; example given for Coastal Spruce–Hemlock Region
Oregon State and private lands	6 m	9 m	Retain enough conifers for basal area of 3.7 m^2 per approx. 305 m of fish stream length; modified by region-specific targets	Retention varies by region; retain non-merchantable trees (only) for the smallest domestic-use streams

TABLE 15.10 *Continued*

Jurisdiction	Riparian reserve width (m)	Management zone(s) width (m)	Management zone(s) retention	Comments
Washington –West State and private lands	15 m (core zone)	Inner zone: 3–26 m Outer zone: 9–20 m	Inner zone: varies by stand class and management option, up to approx. 70% retention Outer zone: 49 dominant and co-dominant trees per hectare	Inner zone may be a reserve if stand is below basal area target for site class; first 9 m of inner zone is reserved for management option to leave trees nearest to the water
Washington – East State and private lands	9 m (core zone)	Inner zone: 14 m Outer zone: 5–17 m	Inner zone: varies by stand class and management option, up to approx. 70% retention Outer zone: 25–49 dominant and co-dominant trees per hectare based on forest type	Example inner zone retention for ponderosa pine timber type: leave 124 trees per hectare to achieve at least 13.8 m^2/ha basal area
California State and private lands	None	23 m, 30 m, or 46 m for adjacent hillslope gradients of < 30%, 30–50%, and > 50%, respectively	Retain ≥ 50% of canopy overstorey and understorey; retain ≥ 25% of overstorey conifers	
Idaho State and private lands	None	23 m	Retain (1) 75% of the existing shade over the stream, (2) all non-merchantable trees, and (3) 91 trees per hectare for streams < 3 m wide	These are streams with domestic water use or important for fish habitat Entire management zone is machine-free
Montana State and private lands	None	1. 15 m where adjacent hillslope gradient is < 35% 2. 30 m in steeper-sloped areas	1. Retain 217 trees per hectare of ≥ 20.3 cm dbh 2. Retain 50% of trees > 20.3 cm dbh	No clearcutting within 15 m of any stream, lake, or wetland Entire management zone is machine-free

TABLE 15.11 *Summary of riparian standards and management practices in northwestern United States for small streams without fish and (or) not used for domestic water supply (FPC/FRPA equivalent class S6 streams, and some class S5 streams) (reserve and management zone widths are converted from measurements in feet and usually rounded to the nearest metre)*

Jurisdiction	Riparian reserve width (m)	Management zone(s) width (m)	Management zone(s) retention	Comments
U.S. Department of Agriculture Forest Service Region 6 (Pacific Northwest)	Perennial: 45 m up to 2 times stand tree height Non-perennial: Greater of 30.5 m or 1 times stand tree height	None	N/A	Perennial: Some harvesting permitted beyond 45 m from stream where 2 times tree height implemented
U.S. Department of Agriculture Forest Service Region 10 (Alaska)	1. Variable width for streams with downstream impact potential 2. None for streams with low downstream impact potential for fish habitat	1. None 2. No specified management zone	Unspecified	1. Buffers based on professional site assessment and judgement 2. Applies to perennial and non-perennial streams; recommendations and practice rules similar to FPC
Alaska State lands	None	30.5 m	Non-merchantable trees	Alaska standards vary by region; example given for Coastal Spruce–Hemlock Region
Alaska Other public lands	None	30.5 m	Non-merchantable trees	Alaska standards vary by region; example given for Coastal Spruce–Hemlock Region
Alaska Private lands	None	Minimum of 8 m up to riparian vegetation limit; maximum of 15 or 30.5 m depending on 12% gradient break	Non-merchantable trees for larger streams only (unconfined streams > 4 m wide; incised streams > 2.4 m wide)	Alaska standards vary by region; example given for Coastal Spruce–Hemlock Region
Washington – West State and private lands	1. Perennial: 15 m for lowermost 152.4 m (500 ft) and at tributary junctions 2. 17 m at headwater springs 3. 15 m at groundwater seeps 4. Non-perennial: None	No additional management zone	N/A	1. No clearcutting > 50% of stream length No harvest on alluvial fans All streams have a machine-free zone 9.1 m wide
Washington – East State and private lands	None	1. Perennial; springs; seeps; tributary junctions: 15 m 2. Non-perennial: no management zone specified	1. Retain a basal area of ≥ 13.8 m^2/ha 2. 9.1-m machine-free zone only	No clearcutting alluvial fans Retain a basal area of ≥ 13.8 m^2/ha All streams have 9.1-m machine-free zone

TABLE 15.11 *Continued*

Jurisdiction	Riparian reserve width (m)	Management zone(s) width (m)	Management zone(s) retention	Comments
Oregon State and private lands	1. 6 m for streams > 0.056 m^3/s discharge 2. None for smaller streams	1. 9 m for streams > 0.056 m^3/s discharge 2. None for smaller streams	1. Retain 10 or more conifers ≥ 20.3 cm dbh plus non-merchantable trees per 305 m of stream 2. Retain non-merchantable vegetation within 3.1 m of the channel in some regions	1. Relates to FPC class S5 streams and larger class S6 streams 2. Relates to small FPC class S6 streams including non-perennial streams; no retention required in Coast Range and West Cascades regions; no RMA or retention required for small ephemeral channels without fish
California State and private lands	None	1. Within 305 m of fish habitat or with other aquatic habitat: 15–30.5 m 2. Streams that can transport sediment/debris: RPF determines management zone 3. Other streams: None	1. Retain ≥ 50% total forest cover including ≥ 25% of overstorey conifers 2. Retain 50% of understorey 3. No specified retention	1. Management zone widths based on adjacent hillslope gradient 2. Machine-free zones 8–15 m wide depending on adjacent hillslope gradients
Idaho State and private lands	None	1. Connected to domestic-use or fish streams: 9 m 2. Locally designated streams of concern: 15 m 3. Minor, disconnected streams: 1.5 m	Retain all hardwood shrubs, non-merchantable conifers, grasses Entire management zone is machine-free	These streams may contain marginal fish habitats and "a few fish"
Montana State and private lands	None	1. Flow more than 6 months per year and direct tributaries to fish streams: 15–30 m depending on hillslope gradient break of 35% 2. Flow less than 6 months per year and connected to other waters, or more than 6 months and disconnected: 15–30 m (as above) 3. Flow less than 6 months per year and disconnected: 15 m	1. Retention as for fish streams 2. Prescription as for fish streams but retain one-half the number of trees = 109 per hectare 3. Retain non-merchantable trees and shrubs	Entire management zone is machine-free for all streams

the significance of some features of the drainage network, such as tributary junctions and perennial reaches flowing directly into fish-bearing waters. For example, Washington has opted to protect such sites in the western region of the state with riparian reserves, whereas management zones with basal area tree retention targets protect perennial streams east of the Cascade Mountains (Tables 15.10, and 15.11). Other jurisdictions, such as Alaska, California, and Montana, recognize terrain slope and channel-hillslope connectivity as important management factors and provide riparian buffers or increase the width of management zones accordingly. For example, Montana doubles the width of its riparian management zones from 15 to 30 m when the steepness of adjacent side slopes exceeds 35%. California requires management zones 23, 30, or 46 m wide where adjacent hillslope gradients are less than 30, 30–50, and greater than 50%, respectively (Tables 15.10, and 15.11).

California, Montana, and Idaho do not employ no-harvest reserves around streams; instead, management zones with retention requirements are in place. These zones include requirements for stream shade. For example, Idaho requires that 75% of the original shade is retained after harvesting adjacent to "important" fish-bearing streams or streams used for domestic water supply. California requires 50% of streamside canopy retention, including 25% of the shade provided by conifers, regardless of fish-bearing status or stream size (Tables 15.10, and 15.11).

For non-fish-bearing streams, management zone widths and tree retention in California and Montana also vary according to the ability of streams to transport sediment and debris. In California, this is determined by a professional forester.

Identifying small streams capable of affecting reaches downstream from those with little potential to do so involves some subjectivity; however, in Montana, this potential is decided according to discharge thresholds, whether the streams are perennial or seasonal, and whether they are connected directly to the drainage network further downslope (Tables 15.10, and 15.11).

Because the management zones and retention requirements for California, Montana, and Idaho are not specifically tied to stream size, the associated riparian tree retention requirements are higher than those specified in regulation for class 4–6 streams in British Columbia.

Increased knowledge of the importance of small streams, plus efforts to address declining salmon populations and restore riparian forest stands, has resulted in increasingly complex riparian management rules in Washington and Oregon (Cashore 2001). With the introduction of the *Forest Practices Rules* in 2001, Washington currently has the most conservative riparian tree retention requirements for smaller streams among all state jurisdictions. These rules require riparian reserves for all fish-bearing and domestic-water streams more than 2 ft (approx. 0.7 m) wide, and require a core, no-harvest reserve zone immediately adjacent to the stream irrespective of stream size; therefore, regulation requirements in Washington well exceed those for the smallest fish-bearing streams (class S4) and for non-fish-bearing streams (classes S5 and S6) in British Columbia; however, streams less than 0.7 m wide are not covered under the Washington rules.

Washington's complex riparian management system has three classes of water bodies. These are: (1) class S or "shorelines of the state," which includes large rivers, lakes, and marine shores; (2) class F, which covers fish-bearing streams or domestic-water-use streams; and (3) class N, which includes all other streams and is subdivided into streams that flow perennially (Np) and those that flow seasonally (Ns). All classified streams have three separate riparian zones: (1) a bank-side core reserve either 9 or 15 m wide, depending on whether the stream is in the eastern or western regions of the state, respectively; (2) an inner zone next to the core with tree retention targets; and (3) an outer management zone with yet different rules.

Each stream class may be further subdivided into as many as five site classes depending on the makeup of the riparian forest. The widths, tree retention requirements, and other practices in the inner and outer management zones also vary according to site class. Site classes have been defined to maintain the structure and species composition of natural riparian stands or to rehabilitate affected sites to historic conditions. For example, where the existing forest of the core zone plus the inner zone falls below the target basal area objectives associated with the site class, the inner zone also becomes a no-harvest riparian reserve. This is called the "no management option" for the inner zone. Together with a 15 m wide core zone, this could add, for forest Site Class I in western Washington, an additional 25 m wide reserve for streams 3 m or less wide, and 30 m of reserve for streams 3 m or more wide. Where existing riparian stands meet target basal area objectives, other management options exist for the inner and outer zones. For example, one option where the smaller trees of a stand can be felled is called "thinning from below."

Although Washington's riparian management rules offer relatively high levels of stream protection, the American Fisheries Society (2000) has criticized them as being too complicated and difficult to implement. In Oregon, riparian management rules are not quite as complex, but are still wide-ranging and vary according to region of harvest (Tables 15.10 and 15.11).

The wide range of approaches for riparian management in the Pacific Northwest appears to reflect outcomes influenced by local landscapes, the history of land use management and its effects on the current condition of riparian forests and streams, varying habitat protection priorities and prerogatives in balance with social and economic values, and different solutions to the challenges of administration and implementation. Ideally, riparian management should be simple to implement, operationally flexible, applied on the basis of local assessments with attention to watershed-scale physical and biological linkages, and guided by conditions in watersheds that are unaffected by forest management. For riparian management to be ecologically sustainable, some reviewers have stressed that it must also be ecologically precautionary (Young 2001); however, what is considered precautionary versus too risky is subject to interpretation. In spite of this variation, all management systems attempt to reduce the well-known potential effects of forest practices on the condition of streams and other water bodies.

FORESTRY-RELATED EFFECTS ON RIPARIAN AREAS

Nearly 50 years of research information is available on the effects of forest harvesting—particularly riparian harvesting—on streams and stream-riparian functions from both short-term and long-term studies (see Chapman 1962; Murphy et al. 1986; Hall et al. 1987; Salo and Cundy [editors] 1987; Hartman and Scrivener 1990; Bisson et al. 1992; Hogan et al. 1998; Young 2001; Broadmeadow and Nisbet 2004; Tschaplinski et al. 2004). Collectively, many studies have generated information on: forestry-related alterations to water temperature regimes; introduction of fine sediments; channel bedload dynamics; LWD sources, dynamics, and functions; channel bank stability and erosion; inputs of fine organic matter, nutrients, and pollutants; primary productivity; macroinvertebrate abundance and community composition; and fish populations and habitats (see Gregory et al. 1987; Hartman and Scrivener 1990; Naiman et al. 1992, Hartman et al. 1996; Hogan et al. 1998; 2000, 2002; Young 2001).

Related to this body of research, numerous studies and reviews have addressed the issue of riparian buffer width and aquatic ecosystem protection (Forest Ecosystem Management Assessment Team 1993; Castelle et al. 1994; Young 2001; Broadmeadow and Nisbet 2004). No definitive width of riparian reserve or buffer will protect streams and other water bodies from every possible impact in all situations. Different physical and biological attributes of streams and other aquatic ecosystems respond differently to riparian forestry according to the influence of climate, geology, natural disturbance regimes, channel type, aquatic communities, and channel interconnections within basins (Vannote et al. 1980; Gregory et al. 1987; Poff and Ward 1990).

Forest harvesting, roads, and other related activities can result in both direct and cumulative effects to streams and riparian areas that affect the overall integrity of these systems and, ultimately, form and function. Because streams and their riparian areas integrate much of the upslope impacts that forestry operations and natural processes may cause, discussions about the effects of forestry operations on streams and the associated riparian areas are much broader than the focus of this chapter. As such, many, if not most, other chapters in this compendium provide details of how various watershed-level effects influence riparian areas. Specifically, forestry effects on LWD supply, landslides, sediment, and channel bank strength are detailed in Chapters 8 ("Hillslope Processes"), 9 ("Forest Management Effects on Hillslope Processes"), and 10 ("Channel Geomorphology: Fluvial Forms, Processes, and Forest Management Effects"). Background on sediment (turbidity and total suspended solids) and temperature as water quality parameters is given in Chapter 12 ("Water Quality and Forest Management"). Measurement techniques for some of these parameters are covered in Chapter 17 ("Watershed Measurement Methods and Data Limitations"). These chapters and others provide detailed discussion of how forestry affects various watershed elements.

In this section, we focus on how forest management directly affects streams and riparian areas with an emphasis on information generated within British Columbia. Three broad and interrelated categories of forestry-related effects on riparian areas include: (1) physical habitat structure alterations, (2) trophic responses, and (3) temperature-related shifts. These categories, separately and in combination, can have different effects on fish, depending on species, life stage, and distribution in freshwater (Hartman and Scrivener 1990). Population and habitat responses to harvest practices are complex. In addition, not all outcomes for some fish species, particularly anadromous salmon, which spend a part of their life cycle in marine environments, can be interpreted solely from processes occurring in freshwater and the effects of forestry on these processes. Long-term trends in fish abundance, especially for anadromous salmon, may be confounded by changes in climate, ocean conditions, and fisheries management strategies (Tschaplinski et al. 2004) and are therefore often difficult to interpret in terms of land use management.

Physical Habitat Alterations

Riparian forest practices can result in increased input of fine sediments (sand and pea-sized gravel) into streams through increases in streambank erosion as a consequence of loss of root strength following tree harvest. Between 2 and 5 years after harvest, streambank erosion increased along nearly 2 km of Carnation Creek that was subjected to clearcut riparian harvesting, compared to erosion observed within a variable-width riparian buffer (2–70 m wide) 1.3 km long (Hartman and Scrivener 1990; Tschaplinski 2000; Tschaplinski et al. 2004). Within 5 years after clearcut riparian harvesting, erodible streambanks collapsed as roots from harvested trees decayed (Hartman et al. 1987). Sediments eroded and were transported downstream by floods, with deposition occurring in the lowermost stream areas and upper estuary used by chum salmon (*Oncorhynchus keta*) (Hartman et al. 1987; Scrivener and Hartman 1990). Accumulation of these fines in the streambed was associated with the decline in the survival of chum salmon eggs from 20 to 11% in the depositional areas (Scrivener and Brownlee 1989).

Problems associated with fine sediments can also result from riparian harvesting through exposure of bare soil by machinery operation, from roads and stream crossings, and from the mineral soil exposed to rain at the base of retained riparian trees overturned by windthrow (Chatwin et al. 2001; Tripp et al. 2009). For example, suspended sediment levels downstream of logged areas were 5–10 times higher than levels in unharvested reaches during peak spring flows in Centennial, Donna, and upper Slim Creeks in the Slim-Tumuch study in central British Columbia (Brownlee et al. 1988).[3] Fine sediments were mobilized from the cut-and-fill slopes of forestry roads, and from skidder trails located near streams (Brownlee et al. 1988).[4]

Channel disturbances also result from cross-stream falling and yarding (Hartman et al. 1987; Brownlee et al. 1988; Hartman and Scrivener 1990). This non-directional falling and near-stream skidding caused the greatest channel disturbances observed in the Slim-Tumuch study. These disturbances were progressively reduced by directional falling and skidding, selective riparian harvest (partial retention buffers), and riparian reserves (Brownlee et al. 1988).

Increased amounts of fine sediments in streambeds can affect benthic macroinvertebrate abundance (Culp et al. 1986). Sediment deposition in areas downstream of logged reaches in the Slim-Tumuch study was strongly associated with reductions in benthic invertebrate densities, particularly in riffles (Brownlee et al. 1988).[5] In one stream, invertebrate drift (originating from the benthos) was also lower in the logged reach than in control reaches.

Channel bank erosion as a consequence of riparian harvesting (Figure 15.9) can also destabilize LWD and result in streambed mobilization and increased rates of channel scour and deposition, which ultimately affect fish populations. In-stream LWD at Carnation Creek, primarily of riparian origin, was mobilized as a result of streambank erosion and collapse, which contributed to changes in channel configuration within 5 years after harvesting was initiated (Toews and Moore 1982). Increased streambed mobility was associated with a nearly 50% post-harvest decline in the survival of coho salmon

3 Slaney, P.A. 1975. Impacts of forest harvesting on streams in the Slim Creek watershed in the central interior of British Columbia. B.C. Min. Environ., Fish Wildl. Br., Victoria, B.C. Presented at Forest Soils and Stream Ecology, a program (FP 2453, May 1975) sponsored by Assoc. B.C. Prof. For. and Univ. British Columbia Fac. For. and Cent. Contin. Ed. Unpubl. report.

4 Ibid.

5 Ibid.

FIGURE 15.9 *Near-stream practices: harvest of streambank tree. (Photo: R.G. Pike)*

(*O. kisutch*) eggs in the clearcut riparian treatments (Holtby and Scrivener 1989).

Watershed-level forestry can also affect channel structure and aquatic habitats irrespective of site-level riparian practices. The magnitude of these effects may have long-term implications. Debris flows originating in steep, logged gullies greater than 1.5 km upstream from anadromous salmon habitats at Carnation Creek occurred shortly after forest harvesting and caused the most pronounced changes to the stream channel and aquatic habitats (Hartman and Scrivener 1990; Hogan et al. 1998).

These storm-triggered debris flows deposited large volumes of logging-associated woody debris and inorganic sediments into the stream channel where the materials were carried rapidly downstream into the riparian clearcut treatments inhabited by anadromous fish. Large logjams and associated sediments deposited by the debris flows moved progressively downstream, passed through the riparian buffer treatment, and eventually reached the stream mouth nearly two decades after the mass wasting events occurred (Tschaplinski et al. 2004). These processes overwhelmed the effects of the riparian management treatments. Major physical changes resulted and are continuing to occur, such as channel widening by two- to threefold, further accelerated scour and deposition processes, loss of stable LWD, and in-filled pools (Hogan and Bird 1998; Hogan et al. 1998;).

Outcomes associated with mass wasting at Carnation Creek and elsewhere represent longer-term, basin-wide processes that point to critical linkages between steep hillslopes and the stream channel network. These linkages are more important in areas of steep terrain where the channel network is closely coupled to the hillslopes. Although the volume of landslide material increased by 12-fold after logging at Carnation Creek (Hartman et al. 1996), much of this material did not enter the channel network. By contrast, in steep and unstable terrain on Haida Gwaii, many small streams have narrow floodplains; therefore, hillslope processes and the stream channel network are closely linked.

Fish-Forestry Interaction Program research on Haida Gwaii quantified large increases in hillslope instability and landslide rates caused by forestry operations in steep terrain. Mass wasting rates increased by 15-fold in areas with forestry operations when compared to areas without forestry-related activity (Schwab 1998). Compared with unharvested sites, the area affected by landslides alone increased by 43 times because of clearcutting, and by 17 times because of problems associated with forestry roads. Correspondingly, the volume of mass-wasted materials attributed to clearcuts and roads increased by 46 and 41 times, respectively (Schwab 1998). About 39 and 47% of the total volume of sediment and woody debris generated by landslides on Haida Gwaii entered streams in unlogged and logged terrain, respectively (Rood 1984). Forestry operations in steep, sensitive terrain where annual precipitation is high clearly require attention.

Recognition of watershed-scale linkages has resulted in increased research and management attention regarding natural processes and management practices in headwater catchments. For example, a multi-agency study of the outcomes of the Prince George District Manager policy for riparian management of class S4 streams was carried out. This B.C. Ministry of Forests and Range policy required the implementation of a 5 m wide machine-free zone adjacent to the stream, retaining all non-merchantable vegetation plus 10 merchantable conifers per 100 m of channel length, and maintaining 50–70% of the pre-harvest levels of riparian shade (www.for.gov.bc.ca/hre/ffip/PGSSP.htm). To achieve management objectives, most of the tree retention occurred within 10 m of the channel. The streams studied were small, first-order watercourses (less than 1.5 m wide), with gradients less than 12% and channel morphologies consisting primarily of riffle-and-pool sequences. A paired, before-versus-after treatment, control-versus-impact experimental design was used to determine the temporal, geographic, and among-stream differences across three geographically distinct areas.

The biological and physical variables measured over time and space included: summer and autumn water temperatures, channel substrate textures, morphometrics and in-stream wood, sources of erosion, riparian litter fall, stream shade and solar radiation exposure, benthic invertebrates, invertebrate drift, periphyton accrual, water chemistry, nutrients, downstream delivery of organic material, and fish community response.

Short-term findings of the Prince George study indicated that fine-sediment generation was effectively managed by riparian practices, although fines from roads and skid trails entered the channel network at stream crossings. Concerns were also low regarding the future outcomes for inorganic nutrients, periphyton, and dissolved organic matter. However, moderate-level concerns were noted for long-term channel morphology integrity and benthic invertebrates, and high concern was noted regarding long-term LWD supply, stream shade, and litter fall, given the level of riparian retention applied (B.C. Ministry of Forests and Range et al. 2007).

Trophic Changes

Stream communities and the associated food webs are driven by primary production (autotrophic production by algae) based on the direct incorporation of solar energy, and by decomposition of organic materials including leaf litter from riparian vegetation (Cummins 1974; see Chapter 13, "Stream and Riparian Ecology" and Chapter 14, "Salmonids and the Hydrologic and Geomorphic Features of Their Spawning Streams in British Columbia" for related information). Of these two major trophic pathways, the one that predominates depends on the availability of direct solar radiation, water chemistry, type and availability of organic material of riparian origin, and several other factors. These variations will determine the community composition of aquatic invertebrates and the relative abundance of those species that feed directly on benthic algae, those that depend on leaf litter and other organic materials decomposed by aquatic microbes, those that use both food sources, and the predators of all of these types (Hawkins and MacMahon 1989; Merritt and Cummins 1996). Although fish species in northwestern North America are generalist predators on aquatic and riparian invertebrates (Hyatt 1979; Tschaplinski 1987, 1988), forestry practices that influence the abundance and availability of these prey are important for determining fish abundance, distribution, growth, and survival.

Riparian harvesting can increase aquatic primary productivity and benthic macroinvertebrate biomass (Newbold et al. 1980; Kiffney and Bull 2000) as well as change the composition of the benthic community (Richardson et al. 2002, 2005); however, research results have varied substantially. For example, Culp and Davies (1983) concluded that benthic macroinvertebrate populations were reduced in Carnation Creek in areas where riparian clearcutting had recently occurred. The reductions were attributed to reduced leaf litter input and retention, and increased erosion, transport, and deposition of sand in the benthos. Culp and Davies (1983) also reported that post-harvest changes in periphyton were small because of phosphorus limitation. In contrast, Richardson et al. (2002) found up to fourfold increases in algal biomass relative to controls (in some seasons) at sites subjected to different riparian management treatments, some of which included riparian reserves 30 m wide. The highest amounts of algae were found in streams with reserves only 10 m wide and those that were clearcut to the banks. Richardson et al. (2002) reported that, when compared with unharvested controls, the densities of midge larvae (Chironomidae) in their experimental treatments in southwestern British Columbia increased in parallel with increased amounts of algae associated with riparian clearcuts and 10 m wide reserves. Also, with decreasing amounts of streamside protection, shifts occurred within the benthic invertebrate community toward more generalist taxa, such as the mayflies *Baetis* and *Ameletus*. Litter input rates were maintained from 10 m wide and 30 m wide riparian reserves at levels similar to controls. At the same time, organic litter input rates declined to about 10% in clearcut sites, when compared with streams having some forest cover.

The consequences of these changes for fish populations and riparian management options remain unclear. Fish biomass and salmon smolt abundance may increase following riparian harvest (Connolly and Hall 1999; Tschaplinski 2000; Tschaplinski et al. 2004); however, the duration of these increases has yet to be determined unequivocally. Juvenile coho salmon growth and smolt production increased immediately after logging at Carnation Creek, but these shifts appeared strongly related to increases in water temperature rather than the consequences of increased food abundance. Elevated temperatures caused substantial shifts in the ecology of coho salmon at Carnation Creek. Warmer conditions (approximately 1°C overwinter) increased coho salmon egg incubation rates, resulting in earlier emergence in spring, a longer season of summer growth, larger-sized fry entering the first winter (11 mm longer on average), and higher overwinter survival attributed to larger size. Consequently, higher levels of smolt production have been sustained in Carnation Creek for nearly three decades (Tschaplinski et al. 2004). The ecological implications for fish of even modest forestry-related temperature changes remain unclear. The same water temperature increases at Carnation Creek have allowed more juvenile coho to transform into smolts after just 1 year of growth in freshwater compared with the pre-harvest situation, where about 50% of the population required an additional year to grow to smolt size. The shift to a majority of 1-year-olds may have implications for poor cohort survival in marine environments in years when ocean conditions are unfavourable (Tschaplinski 2000). Furthermore, any short-term or medium-term responses by fish to trophic regime shifts in Carnation Creek must be viewed in the context of other factors influencing ecosystem features and functions; for example, physical habitat alterations associated with forest practices in riparian areas and on hillslopes. For further information on the cumulative effects of these factors among a number of fish-forestry interactions studies, see www.for.gov.bc.ca/hre/ffip/index.htm.

Riparian Management and Stream Temperature

Water temperature controls chemical and biological processes that importantly influence aquatic ecosystems. Several authors have reviewed how stream temperature varies in both space and time and they should be consulted for a more detailed description of the environmental variables that control water temperatures (e.g., see Chapter 12, "Water Quality and Forest Management," Chapter 17, "Watershed Measurement Methods and Data Limitations," and Chapter 19, "Climate Change Effects on Watershed Processes in British Columbia"; Beschta et al. 1987; Moore et al. 2005). In brief, stream temperature varies daily, monthly, and seasonally because of changes in the sources of energy available to heat water. These energy sources include: longwave and shortwave radiation; sensible and latent heat from the atmosphere; conduction from the streambed; and advective inputs from groundwater, hyporheic, and tributary inflows (see Figure 1 in Moore et al. 2005). Channel size and shape influence the sensitivity of streams to these heat fluxes, with wide, shallow streams being more sensitive to heating than deep, narrow streams of a similar discharge. Generally, stream temperatures increase with decreasing elevation (i.e., further distance from headwaters), although there are exceptions in systems with lakes and wetlands where cooling can occur downstream of these tributary water sources.

Forest management affects stream temperature directly through the removal of shading vegetation and alteration of riparian microclimate (Figure

15.10), and indirectly through channel widening as a consequence of channel destabilization caused by altered streamflow, LWD, and sediment regimes. Riparian harvesting increases solar radiation exposure, wind speed, and exposure to air advected from openings, causing increased air, soil, and water temperatures (Moore et al. 2005). The overall effect of riparian harvesting is increased stream temperatures in all seasons, with the greatest increases occurring in the summer (Table 15.12). Removing shading canopy cover, or a proportion of it, may also decrease nighttime minimum temperatures by allowing greater radiation heat loss. In the northern hemisphere, changes in stream temperature are likely larger in the summer, as the intensity and duration of solar radiation is greatest at this time of year.

Direct comparisons between studies in the literature are difficult because of differing treatments (clearcut, partial cut, prescribed burning, buffers), varying watershed characteristics, and most importantly, differing measures of temperature increases in time (e.g., daily maximum, average monthly maximum, annual maximum). In general, the absolute magnitude of stream temperature increase (Figure 15.11) is directly related to the proportion of surface area newly exposed (Gibbons and Salo 1973) or to the amount of shade reduction (Beschta et al. 1987).

FIGURE 15.10 *Class S4 stream with clearcut riparian management area; virtually all trees removed (Chatwin et al. 2001).*

The duration of elevated stream temperatures after timber harvesting depends on local watershed factors and rate of riparian revegetation. Elevated temperatures are reported to persist anywhere from 2–30 years. In the Bull Run Watershed in Oregon, Harr and Fredriksen (1988) observed that elevated annual maximum stream temperatures returned to pre-logged values within 3 years. At the University of British Columbia Research Forest, Feller (1981) observed increases in stream temperature in summer that lasted 7 years as a result of clearcutting, whereas streams subjected to clearcutting and slash burning showed no signs of returning to pre-treatment temperatures during the same period of time. At the H.J. Andrews Experimental Forest in Oregon, Johnson and Jones (2000) found that stream temperatures gradually returned to normal levels 15 years after harvest.

In some streams, recovery may be slowed or unattainable if the channel has widened to the point where shade is no longer the primary determinant of recovering processes (Tschaplinski et al. 2004). Trees of the recovering riparian forest may need to be taller than the original stands to provide effective shade for channels that have widened because of natural and human-caused disturbances.

Riparian management focussed on maintaining water temperature regimes may become ever more important in the future for British Columbia and elsewhere, given the expected global increases in atmospheric temperatures and associated changes in precipitation regimes (Tyedmers and Ward 2001; Pike et al. 2008a, 2008b, 2008c; Spittlehouse 2008; see Chapter 19, "Climate Change Effects on Watershed Processes in British Columbia"). Current predictions indicate that the province may experience substantial increases in mean annual air temperatures (Spittlehouse 2008; see Chapter 19). Mitigating the extent of water temperature increases resulting from forestry operations in riparian areas will likely become an increasing priority, especially in areas where fish and other aquatic species are already near the limits of thermal tolerance and preference.

TABLE 15.12 *Effect of timber harvesting on water temperature increases*

Location	Temperature increase	Measure	Treatment[a]	Reference
H.J. Andrews, Oregon	7°C, summer 2–8°C	Max. Diurnal fluctuation	CC/BB/PC (25% with debris flow)	Johnson and Jones (2000)
West Olympic Peninsula	3.5°C, summer	Avg. max.	Two partially harvested watersheds (7%, 33%)	Murray et al. (2000)
Coyote Creek, Cascades	8°C	Max.	CC	Adams and Stack (1989)
Salmon Creek Watershed	6°C 2°C	Avg. daily max. Avg. daily min.		Beschta and Taylor (1988)
Bull Run Watershed	2–3°C	Annual max.	CC/BB	Harr and Fredriksen (1988)
Alsea, Newport, Oregon	14°F (7.9°C) 28°F (15.5°C)	Avg. month max. Annual max.	CC/BB	Brown and Krygier (1970)
Slim Creek	2–3°C Doubling 4–9°C	Mean temp. Diurnal fluctuation Summer max.	CC	Brownlee et al. (1988)
Carnation Creek	0.7°C, winter 0.75°C, spring 3.2°C, summer	Mean monthly	CC (41%) with 1.8 km riparian CC	Holtby (1988), Hartman and Scrivener (1990), Hartman et al. (1996)
Carnation Creek	0.7°C, summer 2.7°C, 1st summer 1.4°C, 2nd summer	Mean daily Daily max. Daily max.	Herbicide	Holtby (1989)

a CC=Clearcut, BB=Burned, PC=Partially cut

FIGURE 15.11 *The absolute magnitude of change in stream temperature is related to the amount of shade reduction. Shown is a class S4 stream with "clearcut" riparian prescription; non-merchantable and deciduous trees were retained within 5 m of the stream (Chatwin et al. 2001).*

The wide variation in riparian management regimes in the Pacific Northwest and throughout North America has resulted in several summary papers that compare systems among jurisdictions (Blinn and Kilgore 2001a, 2001b; Cashore 2001; Decker 2003; Lee at al. 2004).[6] Comments are often made about which regimes are more environmentally conservative; that is, which ones offer the best levels of streamside protection for aquatic ecosystems. However, the relative effectiveness of the different management systems is difficult to assess because data are not available on the post-harvest environmental outcomes of the standards and practices applied in the different jurisdictions. Similarly, much discussion has occurred on the design of riparian buffers for the protection of different riparian, stream, and aquatic ecosystem components and functions (e.g., Forest Ecosystem Management Assessment Team 1993; Belt and O'Laughlin 1994),[7] but this discussion similarly lacks supporting empirical evidence from field assessments of buffer effectiveness. The Province of British Columbia established the Forest and Range Evaluation Program (FREP) in 2003 to obtain this type of information on post-harvest management outcomes.

Evaluating the effectiveness of forestry practices in British Columbia has become a priority with the implementation of the results-based FRPA, under which a wide spectrum of forestry management practices may be applied, including those pertaining to riparian and watershed management. Since 2005, province-wide assessments of riparian management effectiveness have been conducted on streams managed under the FPC (www.for.gov.bc.ca/hfp/frep/values/fish.htm). These assessments are annual and ongoing. They now incorporate streams managed under the FRPA.

The key questions asked around riparian management and linked management systems are:

- Are riparian forestry and range practices effective in maintaining the structural integrity and functions of stream ecosystems and other aquatic resource features over both short and long terms?
- Are forest road stream crossings or other forestry practices maintaining connectivity of fish habitats?
- Are forestry practices, including those for road systems, preserving aquatic habitats by maintaining hillslope sediment supply and the sediment regimes of streams and other aquatic ecosystems?

Riparian management assessments are focussed on the first two questions and related effectiveness monitoring programs (for soils and water quality) address the third. Effectiveness evaluations are conducted annually in the field on a large sample of streams selected randomly in each British Columbia Ministry of Forests and Range district. Streams must have experienced at least 2 years (winters) post-harvest to allow for climatic and other disturbances to potentially occur. Each site is surveyed by employing an assessment protocol that includes a set of 15 principal riparian, stream channel, and aquatic habitat indicators (Tripp et al. 2009; Table 15.13). This assessment system, called a "Routine Effectiveness Evaluation," is a simplified version of a relatively intensive sampling protocol developed by an inter-agency/university FREP technical team. It is based on information from the scientific literature, a large base of empirical data that included details about 88 harvested and control streams in 10 forested biogeoclimatic zones, and expert opinion to cover gaps (Tripp and Bird 2006).[8] The indicators have built-in thresholds to assess departure from expected conditions in undisturbed, mature forest stands. This approach was adopted for the provincial-scale monitoring program because of practical problems (e.g., logistics, cost, stream inventory limitations)

6 Zielke, K. and B. Bancroft. 2001. A comparison of riparian protection approaches in the Pacific N.W. and British Columbia. Symmetree Consulting Group, Victoria, B.C. Unpubl. report.
7 CH2MHill and Western Watershed Analysts, 1999.
8 Tripp, D. 2005. On testing the repeatability of a routine riparian effectiveness evaluation methodology. B.C. Min. For. Range, Res. Br., Fish-Forestry Interact. and Watershed Res. Program, Victoria, B.C. Unpubl. report.
Tripp, D. 2007. Development and testing of extensive-level indicators and methods for determining if current forestry practices are sustainably managing riparian, aquatic ecosystem, and fish-habitat values. B.C. Min. For. Range, Res. Br., Fish-Forestry Interact. and Watershed Res. Program, Victoria, B.C. Unpubl. report.
Tripp, D. and S. Bird. 2004. Riparian effectiveness evaluations. B.C. Min. For. Range, Res. Br., Fish-Forestry Interact. and Watershed Res. Program, Victoria, B.C. Unpubl. report. www.for.gov.bc.ca/hfd/library/FIA/2004/FSP_R04-036a.pdf (Accessed May 2010).

TABLE 15.13 *Riparian, stream, and aquatic habitat indicators used for the routine-level assessment of riparian management effectiveness evaluations in British Columbia (see Tripp et al. 2009)*

Riparian, stream, and aquatic habitat indicators	
Channel bed disturbance	Aquatic invertebrate diversity
Channel bank disturbance	Windthrow frequency
LWD characteristics	Riparian soil disturbance/bare ground
Channel morphology	LWD supply/root network
Aquatic connectivity	Shade and microclimate
Fish cover diversity	Disturbance increaser plants/noxious weeds/invasive plants
Moss abundance and condition	Vegetation form, vigour, and structure
Fine sediments	

in identifying suitable control sites for reference purposes across all of the administrative classes and geomorphic stream types within each watershed or other defined area (e.g., physiographic region, specified landscape, biogeoclimatic zone, or portion of a defined watershed).

The routine-level assessment was required to cover a large sample of streams economically each year. Before implementation, the assessment was tested experimentally and operationally to ensure that the results were repeatable and consistent with the more quantitative method from which it was derived (Tripp 2007).[9] The evaluation approach assesses biological and physical attributes of stream reaches and the adjacent riparian areas by using a checklist of 15 questions covering the 15 primary indicators (Tripp et al. 2009; Table 15.14).

Each question is answered either "yes" or "no" to represent a pass or fail for the indicator. Before each question can be answered, several additional questions ("sub-indicators") must be addressed. For example, to answer indicator question five ("Are all aspects of the aquatic habitat sufficiently connected to allow for normal, unimpeded movements of fish, organic debris, and sediments?"), observations must determine whether:

1. there are temporary blockages to fish, debris, or sediment movement caused by instream accumulations of debris or sediment;
2. fluvial downcutting in the main channel isolates the floodplain from normal flooding or blocks access to tributary streams or "off-channel" areas;
3. sediment or debris accumulations occur within or immediately upstream of any crossing structure;
4. downcutting below any crossing structure blocks fish movements upstream by any size fish at any time of year;
5. all crossing structures on fish-bearing streams are open-bottomed ones (versus closed-bottom culverts);
6. dewatering over the entire channel width has occurred because of excessive new accumulations of sediment;
7. off-channel or overland flow areas have been isolated or cut off by roads or levees; and
8. water in the stream has not been withdrawn of diverted elsewhere (Tripp et al. 2009).

For indicator question 5, if a problem is identified with any one of these eight sub-indicators, then the main question is answered "no." For other indicators, a "yes" answer may still occur if one or more of the sub-indicators fail (see Tripp et al. 2009).

A total of 53 different observations and measurements must be made before the 15 main questions can be completed. Each site is classified into one of four possible outcomes by the roll-up score of answers out of 15:

1. Properly functioning condition (PFC): 0–2 "No" answers
2. Properly functioning condition, limited impacts (PFC-L): 3–4 "No" answers
3. Properly functioning condition with impacts (PFC-I): 5–6 "No" answers
4. Not properly functioning (NPF): more than 6 "No" answers

Some main questions may not apply (NA) to some

9 Tripp, D., 2007.

TABLE 15.14 *Fifteen main assessment questions that correspond to the 15 indicators of stream riparian function as given in Table 15.13. These questions, ordered in a checklist, are answered "Yes" or "No" or "Not Applicable" (NA). Before each of these questions can be answered, assessors must answer several additional questions ("sub-indicators") that are associated with the main questions (see Tripp et al. 2009 for full checklist and assessment protocol).*

	Indicator main question	Yes	No	NA
Question 1	Is the channel bed undisturbed?	☐	☐	
Question 2	Are the channel banks intact?	☐	☐	
Question 3	Are channel LWD processes intact?	☐	☐	
Question 4	Is the channel morphology intact?	☐	☐	☐
Question 5	Are all aspects of the aquatic habitat sufficiently connected to allow for normal, unimpeded movements of fish, organic debris, and sediments?	☐	☐	
Question 6	Does the stream support a good diversity of fish cover attributes?	☐	☐	☐
Question 7	Does the amount of moss on the substrates indicate a stable and productive system?	☐	☐	☐
Question 8	Has the introduction of fine sediments been minimized?	☐	☐	☐
Question 9	Does the stream support a diversity of aquatic invertebrates?	☐	☐	☐
Question 10	Has the vegetation retained in the RMA been sufficiently protected from windthrow?	☐	☐	
Question 11	Has the amount of bare, erodible ground or soil disturbance in the riparian area been minimized?	☐	☐	
Question 12	Has sufficient vegetation been retained to maintain an adequate root network or LWD supply?	☐	☐	
Question 13	Has sufficient vegetation been retained to provide shade and reduce bank microclimate change?	☐	☐	
Question 14	Have the number of disturbance-increaser plants, noxious weeds, and (or) invasive plant species been limited to a satisfactory level?	☐	☐	
Question 15	Is the riparian vegetation within the first 10 m from the edge of the stream generally characteristic of what the healthy, unmanaged riparian plant community would normally be along the reach?	☐	☐	

streams. For example, question 4 on channel morphology does not apply to a stream whose form is not created by water (non-alluvial streams). Similarly, fish cover attributes (question 6) are not assessed in non-fish-bearing streams.

Research from the Malcolm Knapp Research Forest has shown measurable, forestry-associated alterations to some of the biological and physical attributes of streams and riparian areas, even when riparian reserves 30 m wide are used (Richardson et al. 2002). Therefore, assessments under FREP are not focussed on whether managed streams are left in pristine condition. Instead, assessments of ecosystem function are employed where "properly functioning condition" is defined as the ability of a stream (Figure 15.12) and its riparian area to:

- withstand normal peak flood events without experiencing accelerated soil loss, channel movement, or bank movement;
- filter runoff;
- store and safely release water;
- maintain the connectivity of fish habitats in streams and riparian areas so that these habitats are not lost or isolated as a result of management activity;
- maintain an adequate riparian root network or LWD supply; and
- provide shade and reduce bank microclimate change.

Therefore, it is assumed that natural ecological functions of the habitat will be maintained if changes that are attributable to forestry practices are within an identified range of natural variability over most of the habitat.

By the end of 2008, a total of 1441 streams from randomly selected cutblocks was assessed province-wide, including 690 class S6 (48% of the total), 93 class S5 (6%), 269 class S4 (19%), 300 class S3 (21%), 84 class S2 (6%), and 5 class S1 (< 1%) streams. Although the sample does not include equal representation across the six riparian stream classes, it is considered to well represent the distribution of the different classes of streams on the landscape, as well as the distribution encountered in forestry operations.

FIGURE 15.12 *Stream in properly functioning condition with all riparian vegetation intact. (Photo: R.G. Pike)*

Most harvesting since 1995 in British Columbia has occurred in areas upslope from large, valley-bottom S1 streams. Sixty-seven percent of the sample consists of class S4 and S6 streams. These stream classes have been the focus of most of the debate and discussion on whether British Columbia's riparian management standards provide sufficient streamside protection to small watercourses, which do not receive riparian reserves in regulation.

Results overall showed that 87% of all streams assessed were in one of the three properly functioning condition (PFC) categories, whereas less than 13% were in the not PFC (NPF) category (Figure 15.13). Thirty-eight percent of all streams were found to be properly functioning without caveats, 29% were in PFC with limited impacts, and 20% were in PFC with impacts (Figure 15.14). Most of the 182 NPF streams were in the non-fish-bearing class S6 (131 streams), whereas most of the remainder were in the small, fish-bearing class S4 (Figures 15.14, and 15.15); however, a small number of NPF streams were class S3, and the impacts were frequently associated with catastrophic windthrow in the riparian reserve.

Results summarized by individual indicators show that most indicators passed ("yes" answers) by a substantial margin with the one exception being fine sediments (Figure 15.16). Fine sediments at levels above the identified assessment thresholds affected more than 63% of all streams that could be assessed for this indicator, including all riparian classes, and regardless of the presence of riparian reserves. Fine sediments affected all stream classes partly because a major source of these materials was from roads and stream crossings. These sediments, and those from riparian management-related sources (e.g., windthrow, exposed soil) affected the performance of some of the other indicators such as benthic invertebrates. However, for other indicators (e.g., vegetation form, vigour, and structure) with relatively high frequencies of "no" answers for the small S4 and S6 streams, responses were attributed to low levels of riparian tree retention and high levels of near-stream harvesting activity within the management area (e.g., cross-stream felling and yarding for S6 streams). For streams that scored NPF or were in one of the two intermediate categories, low riparian

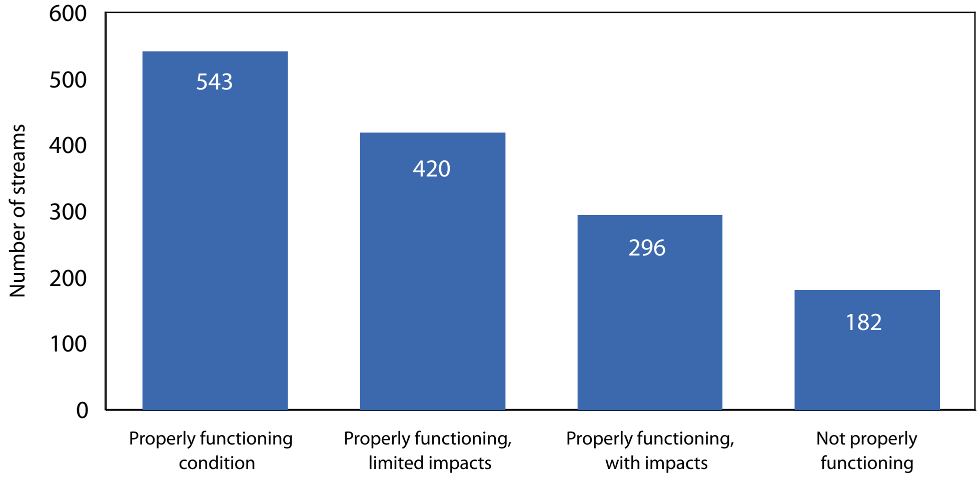

FIGURE 15.13 *Overall outcomes of riparian management effectiveness evaluations under the Forest and Range Evaluation Program for 1441 streams assessed between 2005 and 2008.*

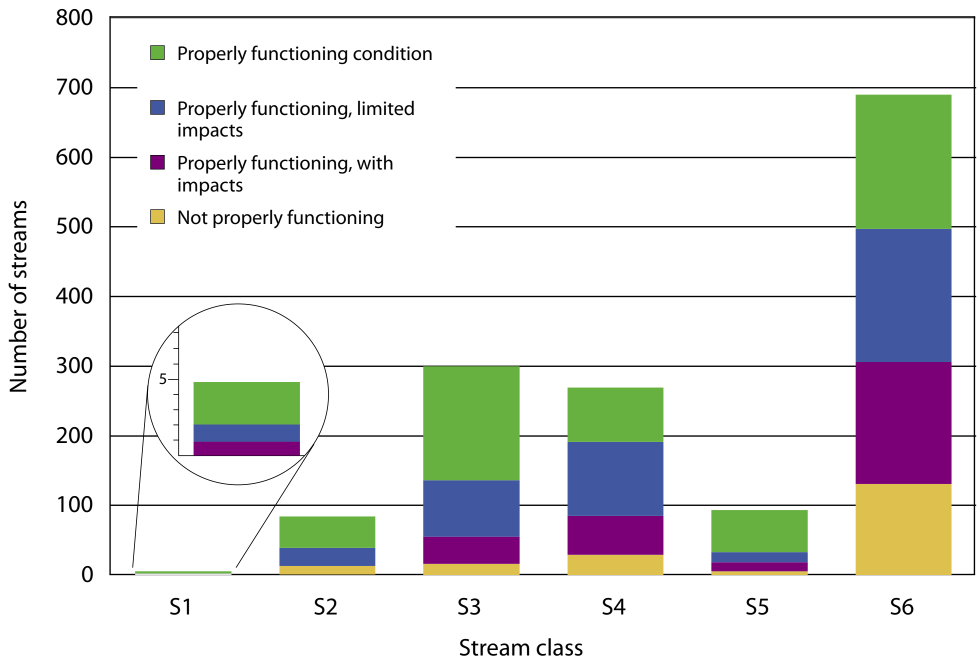

FIGURE 15.14 *Overall outcomes of riparian management effectiveness evaluations by riparian stream class for the 1441 streams assessed under the Forest and Range Evaluation Program between 2005 and 2008.*

FIGURE 15.15 *Class S4 stream with full retention from the streambank up to the top of the gorge (Chatwin et al. 2001).*

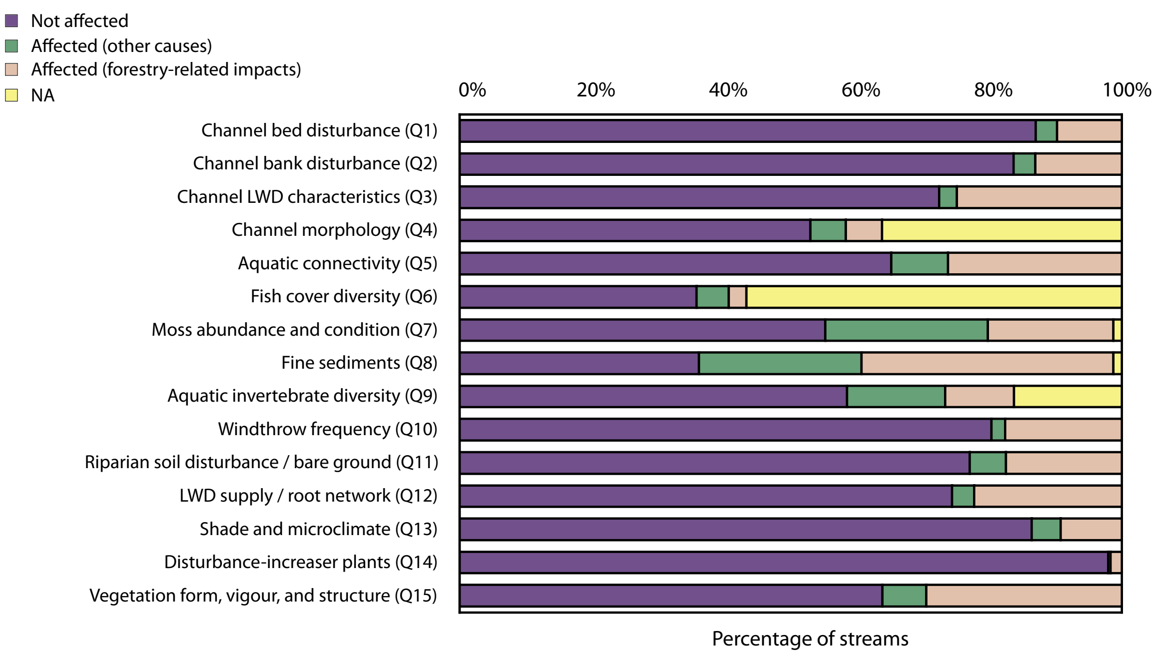

FIGURE 15.16 *Overall outcomes of riparian management effectiveness evaluations by individual indicator for all streams assessed under the Forest and Range Evaluation Program between 2005 and 2008 combined. Yes = indicator pass; No (shaded black) = indicator failure attributed to site-level forestry causes; No (shaded gray) = indicator failure attributed to other causes; White bars are where either an indicator was not applicable (e.g., fish habitat diversity in non-fish-bearing streams), or where the indicator could not be scored.*

tree retention was identified as a main or contributing causal factor for indicator failure 48% of the time, whereas road-related factors affected 35% of the indicator failures as the main agent, and 68% of all failures as either the main or contributing factor. Other important impact causes included windthrow (32% main plus contributing), cross-stream felling and yarding (30% main plus contributing), and livestock-related activities (9% of the main causes).

Not all of the indicator failures were attributed to site-level, forestry-related causes. Impacts delivered from sources upstream contributed to about 21% of the indicator failures. Other indicator failures were related to antecedent conditions outside the range of variation built into the indicators, or to non-forestry-related activities. For example, fine sediments appeared to be naturally abundant in some small, low-gradient S6 streams, particularly in central Interior locations where glaciolacustrine sediments are widespread. Nearly 40% of all "no" answers for the fine sediments indicator were attributed to causes other than site-level forestry (Figure 15.16); however, averaged over all sites provincially, the mean number of indicator failures due to non-forestry-related factors was only 1.1 per stream (Table 15.15).

On average, when forestry-related factors are included, the mean number of indicator failures ("no" answers) was 3.6 per stream, leaving a mean forestry-related increment of 2.5 per stream. The largest increments attributed to forestry occurred in class S4 and S6 headwater streams where 2.5 and 3.4 "no" answers were added for the two classes, respectively. The predominant broad causal factors of low riparian tree retention, road-delivered fine sediments, and cross-stream falling and yarding (S6s) appear to explain the outcomes for these smallest streams, whereas road-delivered fine sediments and windthrow-related impacts were common sources of problems for larger fish-bearing streams with riparian reserves (classes S1–S3) and for the large non-fish-bearing class S5 streams (Table 15.15). Larger streams appear to be relatively well managed. On average, forestry added only 0.9–1.0 "no" answers for the largest streams (classes S1 and S2), and 1.4 and 1.6 "no" answers for classes S3 and S5, respectively.

These results, together with the identified causal factors, have initiated discussions on how the environmental outcomes of riparian management in British Columbia might be further improved. Anticipated problems with some class S6 and S4 streams and the associated frequencies of occurrence have been systematically identified and statistically assessed. However, the FREP assessments also demonstrate that many S6 and S4 streams scored well when certain practices were applied. Preliminary observations indicate that the number of "no" answers related to riparian management can be substantially reduced if the following three practices are followed, particularly within the riparian management zones of small streams.

1. Limit introduction of logging debris and riparian management area–related sediments into channels.
2. Limit physical contact with streambanks and streambeds when falling and yarding around class S6 streams; fall and yard trees away from the channel wherever possible.
3. Retain more vegetation more frequently around class S4 streams and important S6 streams.

For example, problems were frequently encountered when non-merchantable trees and understorey vegetation (at a minimum) had not been retained in riparian areas. Fine sediment generation from roads and crossings was also frequently encountered.

TABLE 15.15 *Mean number of indicator failures ("no" answers) per riparian class of stream attributable to forestry-related and non-forestry-related causes*

Stream class	No. streams	Total "no" answers	No. non-forestry "no" answers	Unhealthy (NPF) without forestry (%)	Unhealthy (NPF) with forestry (%)	Mean non-forestry condition (no. "no")	Mean condition with forestry added (no. "no")	Mean impact increment with forestry (no. "no")
S1	5	14	9	0	0	1.8	2.8	1.0
S2	84	217	142	0	1.2	1.7	2.6	0.9
S3	300	803	397	0	5.3	1.3	2.7	1.4
S4	269	1011	352	0	10.8	1.3	3.8	2.5
S5	93	228	81	0	5.4	0.9	2.5	1.6
S6	690	2904	555	0	19.0	0.8	4.2	3.4
All	1441	5177	1536	0	12.6	1.1	3.6	2.5

However, these problems can be addressed using well-known streamside retention and sediment management practices. The more frequent implementation of these techniques will likely improve outcomes for small streams.

The discussion of best management practices versus those associated with problems should continue and expand beyond the broadly identified issues of riparian retention, road-related sediment, and harvesting or range activities within riparian management areas. To identify which practices are the most suitable for specific situations, several site-specific options need to be discussed with forestry and range practitioners.

Among the many challenges is adapting management to the diversity of streams within the numerically dominant class S6. These streams dominate the lengths of drainage networks and can be relatively large (2.5–3 m wide), perennially flowing watercourses with sufficient hydraulic energy to influence streams, aquatic habitats, and fish downslope. At the other end of the spectrum are the narrow, ephemeral class S6 streams, which may scarcely be 100 m long with barely discernable channel beds, and may not be connected to the rest of the drainage network by surface flow. Identifying appropriate riparian management activities across this broad spectrum of channels will continue to be one of the most challenging aspects of land use management.

Riparian assessments in British Columbia under the FREP are still at a relatively early stage despite the large sample of sites already evaluated. The 1441 sites assessed between 2005 and 2008 form a substantial sample representative of the outcomes achieved under the prescriptive FPC regime, and provide a performance baseline for comparison with streams managed under the results-based FRPA regime.

SUMMARY

Monitoring the responses of streams and riparian areas under FREP will continue and will contribute to incremental improvements to riparian management outcomes in British Columbia. In the immediate future, the effectiveness of riparian management implemented under the FRPA will be the main subject of post-harvest assessments of stream and riparian conditions. Existing riparian and stream channel monitoring in British Columbia provides information in the form of one-time "snapshots" of functional condition 2–12 years after harvesting. These data represent relatively short-term forest harvest effects (Figure 15.17). Research has shown that forestry-related impacts on streams and aquatic habitats may not be fully developed until two decades or more have elapsed, especially in cases where impacts are related to mass wasting in headwater areas and are propagated over time down the stream channel network (Tschaplinski et al. 2004). Therefore, continuous monitoring will have to be conducted over the long term to allow adequate adjudication of the potential long-term effects of forestry activities and thus inform strategies proposed for riparian and watershed management in British Columbia. This long-term perspective is particularly important in a results-based forest management regime where several strategies may be proposed for these purposes.

The debate on how to best manage streams, particularly small streams, will likely continue. Although the implementation of ecologically sound riparian management practices is desirable, actually accomplishing this will pose significant challenges. Several questions will have to be addressed. For example, if some small streams are managed more conservatively by increasing the levels of streamside tree retention to maintain attributes and functions on-site and to provide for aquatic habitats downslope, can this be done on an ecologically sound basis at the watershed level, while also providing some forestry opportunities? Can some forestry opportunities be achieved by re-allocating riparian retention from the riparian reserve zones of some larger streams? Will doing so have undesirable consequences for stream reaches where fish actually live?

Many sound reasons exist for managing within a watershed context. However, we are still learning about how physical processes operate, how these processes are interrelated at larger spatial scales, and how these physical processes interact with biological processes at the watershed level. On the other side of this issue, one notion is that good practices exercised at the site level will likely go a long way towards providing functions at the watershed level. For example, if we provide for shade and sources of instream

FIGURE 15.17 *Clearcut riparian management area with second-growth vegetation. (Photo: R.G. Pike)*

wood, limit ground disturbance in and near riparian management areas, manage roads to minimize sediment introductions to streams, and maintain fish passage, will these site-level actions be sufficient to maintain the integrity of the channel network and its aquatic ecosystems from the rim of the basin to the outlet of the principal stream? Is our knowledge of watershed functions sufficient to provide us with the confidence to achieve desirable outcomes?

Significant research gaps persist about the interactions of forestry practices in regard to LWD dynamics, sediment budgets and routing, water temperature impacts, groundwater–channel interactions, and riparian reserve and management zone design to maintain these functions effectively at the site level. These and other research needs will be accentuated in the future given the mid- and long-term effects of global climate change and its implications for precipitation and temperature regimes, forests, aquatic ecosystems, and watershed management. At the same time as post-harvest effectiveness monitoring continues to provide the important data necessary for adaptive management, additional research information in key gap areas can only benefit operational designs for riparian and watershed stewardship.

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Detecting and Predicting Changes in Watersheds

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INTRODUCTION

Hydrologists and geomorphologists are often consulted to predict or detect the potential effects of forest management activities on watershed processes and streamflow. The resulting evaluations are frequently used to improve forest practices, and in planning-policy adjustments, certification, and risk management. Ultimately, the information provided helps to ensure the appropriate management of watershed processes, which in turn directly influences key values such as drinking water, timber resources, fish, and ecological functioning.

It is challenging to predict change in watersheds that have few or no hydrologic or geomorphic data. Even in areas where suitable data exist, it is often difficult to transfer results beyond watershed boundaries because of scaling issues, the unique characteristics of individual watersheds, and the complexity of the processes involved. The interactions between disturbance and climate variability greatly affect hydrologic response (water quantity and quality) and make prediction of end-states difficult. As a result, a distinct gap can exist between the level of certainty of information that hydrologists and geomorphologists can provide and the certainty of predictions that forest managers seek.

Many approaches are used to detect and predict changes in forested watersheds. These approaches fall within general categories of change detection (i.e., research, monitoring, and modelling) and change prediction (i.e., modelling, watershed assessment). Change can be quantified in terms of the magnitude of change (relative to a given baseline condition) and the direction of change (positive or negative relative to a resource value of interest). These approaches can be grouped into four distinct categories: (1) research, (2) monitoring, (3) modelling, and (4) watershed assessment.

This chapter provides a basic overview of the four overlapping approaches for detecting and predicting changes in forested watersheds. This chapter will provide background for the reader and references to further information. The objective is to provide the reader with sufficient information to allow the selection of the most appropriate method(s) to assess forest management effects.

GENERAL ISSUES AND CHALLENGES

The hydrologic and geomorphic effects of forestry activities (i.e., timber extraction, site preparation causing soil disturbance, stream crossings, road construction, and road maintenance) and natural disturbances (i.e., insect infestations, landslides, windthrow, and wildfire) are frequently the main concerns regarding watershed management. To a lesser degree (but not necessarily of lesser importance) is the use of off-road vehicles and recreational activities that can affect water quality and directly affect fish/aquatic habitat. A key issue is to determine when and how these activities are detrimental or require further watershed-scale or site-level analyses before initiating additional forest development.

Several issues are common to the four approaches outlined in this chapter. In quantifying the potential effects of forest management activities, different approaches are required, depending on the temporal and spatial scale of the question, and the resource of concern. Variability within and among watersheds and watershed response to forest disturbance are common challenges. Fundamental to some methods is the delineation of a reference state, which can be difficult, given continual change in factors (e.g., climate) that drive hydrologic and geomorphic processes. Sometimes, answers are needed at temporal and spatial scales for which data are unavailable. This frequently entails the transfer of results or models developed at a particular temporal or spatial scale to largely different scales (e.g., a different watershed, different region). These factors generally preclude the creation of generic management "rules of thumb" that can be universally applied to watersheds in British Columbia.

Compounding these issues are cumulative watershed effects and difficulties separating forest management effects on watershed hydrology and function from natural disturbance, climate variability, and other anthropogenic effects of land use and development (e.g., recreation, range, agriculture, mining). A cumulative watershed effect (CWE) is the overall impact on a resource, where either a water-related resource is affected or a change in watershed processes generates the impact (Reid 2010). Cumulative effects result from the combined effect of multiple activities over space or time (MacDonald 2000). These effects can manifest if existing adverse conditions increase in magnitude, duration, or frequency, if the sensitivity of the resource is altered, if a new adverse condition is created, or if mechanisms that once moderated impact severity become inoperative (Reid 2010). For CWEs, the evaluation of the cause of change can be difficult to determine, as individual influences often cascade, resulting in impacts that are decoupled in space and time from the event or management activity of interest (Reid 2010).

RESEARCH

Research confirms and builds on our knowledge base of watershed processes and, most importantly, provides an opportunity to serendipitously acquire new knowledge. Research allows for the detection of changes in watersheds and provides background knowledge necessary to predict the potential occurrence and effects of these changes.

In experimental research, the focus is usually on quantifying the effects of a given treatment (e.g., clearcut harvesting) on a hydrologic process (e.g., interception) or quantity of water (e.g., annual water yield, peak flows, low flows). This often involves quantifying the magnitude, direction, and duration of the response. Study designs commonly include a comparison of treated and untreated control units to facilitate the detection of change (i.e., treatment effects). In experimental research, control and treatment units are identical, with the exception of the applied treatment; pre-treatment measurements establish the initial relationship between the treatment and control units. Experimental control provides the basis to determine whether changes in the treatment units have also been observed in the controls, or whether changes are due only to the treatments. As the scale of an experiment increases, it becomes much more difficult to establish treated and control units and to control other factors that can confound an experiment (Schindler 1998).

Replication is the use of repeated treatments to assess the variability of a process and treatment effect outside of a single control-treatment pair (Eberhardt and Thomas 1991). "Replication is used to estimate the variation in response to treatment due to differences in the sites or treatment applications" (Ford 2000:160) and ensure that confidence intervals can be estimated around the treatment response mean (Powers and Van Cleve 1991). "Replication provides an estimate of the experimental error, which is any variation that cannot be explained by the experimental factors (i.e., sampling or measurement error, and natural variation among the experimental units)" (Nemec 1998:12). Without replication, one cannot characterize the variability within an experimental group, and subsequently cannot conduct any statistical analysis of the differences between experimental units. This reduces the research to a simple case study. The other important benefit of replication is that it allows extrapolation from the sample to the other members of the same population. In hydrologic research, the ability to replicate is often limited, particularly at large spatial and temporal scales, and this lack of replication weakens the inferences and generalizations that can be drawn from the results of an experiment (Ward 1971). A common mistake in conducting research is that of confusing the control of events (treatments) with the control of the observational process (Eberhardt and Thomas 1991). "Circumstances in which replication denotes the ability to repeat a treatment should be distinguished from those in which it means taking repeated observations" (Eberhardt and Thomas 1991:54). This leads to the dichotomy between conducting controlled experiments and observing uncontrolled events. (See Schwarz 1998 for further description of studies of uncontrolled events including Impact Surveys and Before/After Control Impact Design.)

Researchers frequently need to determine whether changes are statistically or hydrologically significant. Generally, this line of inquiry employs strategies that will allow testing for differences using a null hypothesis approach. Statistical significance, however, may not be the most relevant method with which to determine the impacts of forestry activities on hydrology. The misuse of tests of statistical significance can confuse interpretation of research data (Johnson 1999).

Forest managers are more likely interested in the magnitude (how large an effect), direction (increase or decrease), and duration (length of time that the effect lasts) of system response, rather than testing for difference using a null hypothesis approach (Carpenter et al. 1998). Recently, the selection and application of appropriate statistical methods has generated considerable controversy in forest hydrology (e.g., Jones and Grant 1996, 2001; Thomas and Megahan 1998, 2001). This controversy has led some researchers to avoid complex parametric statistics, in favour of simpler graphical analysis that shows mean and standard deviation as indicators of change (Jones and Post 2004). Basic statistical methods relating to water resources are well covered by numerous texts. See examples in Table 16.1.

TABLE 16.1 *Selected statistical reference material for further review*

Title	Description/Notes	Reference
Monitoring Guidelines to Evaluate Effects of Forest Activities on Streams in the Pacific Northwest and Alaska	Statistical considerations in monitoring water quality and stream channel conditions	MacDonald et al. 1991
Statistical Methods for Adaptive Management Studies	Many examples in a water resources context including experimental design, studies of uncontrolled events, retrospective studies, and selection of appropriate statistical methods	Sit and Taylor (editors) 1998
Biometrics information: pamphlets and handbooks	Seven handbooks and 60 pamphlets	Various authors; see B.C. Ministry of Forests and Range website: www.for.gov.bc.ca/hfd/pubs/Bio.htm
Statistical Methods in Water Resources	Statistics textbook for hydrologic data analysis, emphasis on non-parametric methods	Helsel and Hirsch 1991

Experimental research approaches used in forest hydrology can be organized along a spatial hierarchy, from smallest research unit to largest (i.e., sample-, plot-, and watershed-scale studies). The spatial scale of the research approach has many implications for research design and subsequently the ability to generalize and make inferences to the broader landscape or conversely to identify key site-level processes. In some instances, it may be advantageous to employ manipulative experiments that allow the examination of system behaviour when pushed outside normal boundaries. This approach can help to isolate important processes or mechanisms that drive system response (Kirchner 2006). Ultimately, the research method selected will depend on the question being addressed (Pennock 2004).

Sample-scale Studies

The smallest scale of hydrologic research occurs on sample-sized experimental units such as soil cores or streambed (benthos) samples. Sample-scale studies are used to overcome the difficulty in measuring processes on larger scales (e.g., evapotranspiration losses from forest stands vs. individual leaves or branches for short time periods). Sample-scale research can be replicated and is amenable to standard statistical analysis. These studies generally provide detailed process information, and are frequently used for model parameterization. Examples of sample-scale research may include the analysis of water repellency in soil samples subjected to different temperatures, or transpiration from small branches under different climatic conditions. The major challenge with the use of sample-scale research results is the extrapolation to the plot and (or) watershed scales (Kirchner 2006; Sidle 2006).

Plot-scale Studies

A plot- or stand-scale study seeks to investigate hydrologic processes at a spatial scale larger than the sample, but where control and replication are still possible. Examples of plot-scale studies include research on hillslope runoff processes (e.g., Buttle and McDonald 2002), where hillslopes are monitored for runoff and soil moisture fluxes in response to precipitation, or the analysis of snow accumulation and melt under tree canopies relative to clearcut openings (e.g., Winkler et al. 2005). Sometimes the results of sample-scale measurements can be integrated into the measurement and modelling of plot-scale processes. Plot-scale studies are also used to evaluate spatial variability of hydrologic processes.

Although replication increases the power of plot-scale research, it may be impossible to locate acceptable replicates because of landscape heterogeneity. The plot-scale approach for watershed-scale research often assumes that results can be scaled up to the watershed level.

Watershed-scale Studies

Watershed-scale studies frequently examine the effects of forest management on streamflow, which provides an integrated response of watershed hydrology to disturbance. Because watersheds provide a convenient unit within which multiple, and sometimes conflicting, values are managed, research ideally would occur at the same spatial scale as management. Watershed-scale studies are generally divided into single- or paired-watershed (also called single- and paired-basin) approaches.

In a single-watershed study design, a watershed is monitored before and after a treatment to determine the effects on watershed function (Whitehead and Robinson 1993). Although this approach requires the monitoring of only a single watershed, the design still does not easily account for changes in climate or other confounding factors that might influence watershed function or response over time. For instance, if climate changes (e.g., Pacific Decadal Oscillation shift) between the pre- and post-treatment monitoring periods, no control is available to help determine which effect is a response to the treatment and which effect is a response to climate variability (Brechtel and Fuhrer 1994). In some cases, however, controls are developed within the watershed of study (e.g., a tributary). An example of a single-watershed study with a nested control design is the Carnation Creek Watershed Experiment (see Hogan et al. [editors] 1998).

The paired-watershed approach is often the preferred method for assessing watershed-scale response to forestry activities (Whitehead and Robinson 1993). The paired-watershed approach involves the use of control and treatment watersheds where both basins are monitored during the pre-treatment phase and a regression relationship is developed to predict a given variable (generally streamflow) in the watershed to be treated. The paired-watershed design can be planned where the watersheds are specifically selected and instrumented for experimental purposes (paired-basin experiment), or existing instrumented watersheds can be used if the watersheds are similar enough (paired-basin study) (Moore and Scott 2005).

After treatment, the magnitude of the treatment effect is assumed to be the difference between the predicted streamflow, using the pre-treatment relationship with the control watershed, and the measured streamflow (Ward 1971). The Upper Penticton Creek Watershed experiment (see Winkler et al. 2003) is an example of a paired-basin experimental approach.

Significant challenges are inherent in the paired-watershed approach. Large watersheds can be more difficult to pair than smaller ones because of the inherent spatial variability in watershed morphology and climate gradients. The differences introduce scatter around the pre-treatment regression line and thus reduce the statistical power of the analysis compared with smaller paired-watershed experiments. An important question for these studies is how long should the watersheds undergo monitoring in the pre-treatment phase. If the period is too short, the experiment can lack satisfactory precision and may not be able to demonstrate a treatment effect (Wilm 1949). If the period is too long, the proposed pre- and post-treatment sampling can make these experiments unnecessarily expensive. Most traditional paired-watershed studies have used annual response variables (e.g., water yield, peak flows) to avoid problems with autocorrelation within the data. The use of annual data, however, reduces the sample size, resulting in a loss of information at the shorter time scales. Its use also necessitates longer pre- and post-treatment measurement periods, which may not answer management questions in a timely manner. Several researchers, such as Troendle et al. (2001), Watson et al. (2001), and Gomi et al. (2006), have therefore explored many strategies to use shorter time step (i.e., sub-annual quantities) data.

Because of the scale of the experiment and the difficulty in isolating the effects of two simultaneous impacts (e.g., harvesting vs. climate cycles), the paired-watershed approach is limited to examining the cumulative effects of change of a single perturbation (Moore and Scott 2005). The traditional paired-watershed approach can be a "black box" unless plot- and sample-scale studies are included to understand treatment effects on hydrologic processes (Sidle 2006). Other research designs (discussed in this chapter) are therefore generally more appropriate for larger watersheds.

Conducting research at the watershed scale can be challenging. One of the greatest concerns is the inability to replicate, which can inhibit the ability to transfer results beyond the research watershed (Alila and Beckers 2001). Additionally, the size of a watershed may also influence the research results, as smaller watersheds generally have greater variability in streamflow characteristics and show a relatively larger impact of land use change than larger watersheds (Pilgrim et al. 1982). Because conducting research at this spatial scale can also be costly, watershed-scale experiments are not routinely initiated in British Columbia. Nevertheless, data from watershed-scale experiments can provide hydrologists and managers with vital information about watershed-scale hydrologic response to forest management practices (Moore 2005; Moore and Scott 2005). Research at this scale is also important for other approaches (e.g., modelling) and to generate data for verifying scaled-up results from sample- and plot-scale studies. In some cases, meta-analyses of multiple paired-watershed experiments (see Bosch and Hewlett 1982; Jones and Grant 1996; Stednick 1996; Jones 2000; Jones and Post 2004) can be very helpful to extrapolate to other conditions and evaluate the variability in response.

Time-series and Spatial-comparison Approaches

Research approaches can also be categorized by temporal and spatial scales. There are two fundamentally different approaches: (1) the time series examines hydrologic variations for a set of units having different management histories, and attempts to use statistical methods to separate climatic variability from a signal associated with changes in forest condition; and (2) the spatial comparison uses a space-for-time substitution to examine the effects of different forest conditions on hydrologic response variables.

Time-series approaches provide a snapshot through time of system behaviour (Powers and Van Cleve 1991) and may be used at the sample, plot, and, less frequently, watershed scales. Studies using the time-series approach select sites along a temporal continuum from the time of (or even before) a given perturbation through different phases of system response (Powers and Van Cleve 1991; Moore 2005). The major assumption of this method is that differences between sites are caused by differences in time since disturbance. This assumption is often weak, as climatic variability through time (e.g., Pacific Decadal Oscillation shift) can mask the signal associated with management (treatment). As well, changes in management practices generally occur through time (Powers and Van Cleve 1991). There are, however, review articles that outline methods for analyzing change in streamflow time series (e.g., Kundzewicz and Robson 2005 and references therein).

The benefit of time-scale approaches over long-term continuous monitoring of watersheds is the ability to replicate treatments across the landscape in a short period of time; however, this benefit comes at the cost of well-designed controls and pre-treatment sampling. As a result, time-scale approaches are not widely used in forest hydrology studies. Nevertheless, time-scale approaches are useful for broader-scale assessments and can be used in developing regionalization and scaling schemes to transfer data from smaller experimental watersheds to larger landscapes. Although these studies have been criticized for weaknesses in design, time-scale approaches try to understand forest management effects at larger spatial scales not addressed by small watershed experiments, and do so in a time frame that supports adaptive management.

Spatial-comparison approaches select treatment units and associated (often adjacent) untreated control sites to examine potential treatment effects. In spatial-comparison studies, careful site selection is essential for controlling as many properties as possible (Swanson and Hillman 1977; Powers and Van Cleve 1991). The assumption is that the treatment and control sites were initially very similar, and that treatment effects caused the differences between them. As no pre-treatment information is available for the treated unit, this assumption may be tenuous (Powers and Van Cleve 1991). In forest hydrology, the spatial pattern of treatments and controls is not random. For planned experiments, variability among experimental units contributes to "experimental error," and can be dealt with via randomization and replication. Randomization controls for the possibility of bias caused by systematic differences among the treatment and control plots, and replication reduces the error term. For example, Gomi et al. (2001) used a spatial-comparison approach to examine the effect of disturbance on woody debris and sediment in headwater streams in Alaska, and used statistical methods appropriate for designed experiments with treatments randomly assigned. However, the spatial clustering of treatments (see Figure 1 in Gomi et al. 2001) means that the effects of disturbance history could be confounded with inherent gradients in catchment morphology, forest and soil characteristics, and climatic conditions across the study region.

Research Approach Summary

The design and analysis of forest hydrology research requires clearly defined goals and objectives for the research project. To this end, clearly defined hypotheses or questions are key to developing an efficient measurement and analysis strategy (Pennock 2004). Predicting a watershed disturbance effect depends on process knowledge (Kirchner 2006; Sidle 2006). Transferring process knowledge (understanding) between spatial or temporal scales is a major challenge for research. This difficulty should be recognized at the outset of a research project, as the available measurement techniques will, in part, determine the ability to move data between scales of interest (Kirchner 2006; Sidle 2006).

MONITORING

Monitoring is the second approach commonly used to detect changes in watersheds. This section introduces the concept of monitoring and refers the reader to additional sources of information on the subject (see Table 16.2). The development of indicators and measures to gauge forest management effects on watershed function are beyond the scope of this short discussion. Methods specifically related to riparian areas are covered in Chapter 15 ("Riparian Management and Effects on Function") and watershed measurement methods and data limitations are covered in Chapter 17 ("Watershed Measurement Methods and Data Limitations").

Monitoring usually means "to describe a variable or variables and track changes over a period of time" (MacDonald et al. 1991). Generally, monitoring is differentiated from research by the lack of controls that research approaches use to distinguish cause and effect. The distinction between the two approaches, however, can be fuzzy, as each involves

TABLE 16.2 *Monitoring reference resources*

Title	Description/Notes	Reference
Monitoring Guidelines to Evaluate Effects of Forest Activities on Streams in the Pacific Northwest and Alaska	Design considerations and monitoring techniques	MacDonald et al. 1991
Guide to Effective Monitoring of Aquatic and Riparian Resources	Parts II and III of this document contain the protocols for measuring specific aquatic and riparian attributes that describe habitat conditions	Kershner et al. 2004
Testing Common Stream Sampling Methods for Broad-scale, Long-term Monitoring	Evaluation of variability in stream habitat sampling methods used by the U.S. Department of Agriculture Forest Service and the Bureau of Land Management monitoring program for the upper Columbia River Basin	Archer et al. 2004
The British Columbia Watershed Restoration Program: Summary of the Experimental Design, Monitoring, and Restoration Techniques Workshop	Synthesis of recommendations for experimental design, monitoring, and restoration techniques	Keeley and Walters 1994
A Review of Protocols for Monitoring Streams and Juvenile Fish in Forested Regions of the Pacific Northwest	Reviews existing and proposed protocols used to monitor stream ecosystem conditions and responses to land management activities in the Pacific Northwest	Stolnack et al. 2005

sequential measurements. At first glance, the concept of monitoring is easy to understand, yet can be difficult to implement if ill-planned and delivered. Defining clear project objectives, selecting appropriate variables and sampling scheme to achieve stated objectives, and establishing a baseline or reference state for the variables of interest are essential for successful monitoring.

Monitoring is typically designed to: (1) inform when the system is departing from the desired state; (2) evaluate the success of management activities; and (3) detect the effects of system disturbances (Legg and Nagy 2006). Although many variables and a broad spectrum of instruments are available to collect quantitative data, monitoring is also based on qualitative measurements (e.g., descriptive assessments or use of repeat photographs).

When statistical analyses will be used to quantify detectable changes, it is important to consider sample size (and the associated statistical power) at the outset of monitoring study design (Loftis et al. 2001). Monitoring projects can be divided into the following categories (adapted from MacDonald et al. 1991):

1. Trend: Measurements at regular intervals to determine the long-term trend in a particular variable.
2. Baseline: Description of conditions to establish baseline data for planning or future comparisons.
3. Implementation: Assessment of activities to determine whether they were carried out according to plans. Generally this entails few, if any, measurements. An example would be determining whether riparian-zone widths comply with regulations.
4. Effectiveness: Evaluation of the degree to which a specified prescription had the desired effect. For example, determining whether a riparian zone maintained water temperatures during mid-summer.
5. Project: Assessment of the impact of a particular project on a given variable. For example, the impact of road construction and (or) harvesting of a cutblock on water quality, involving upstream/downstream data collection.
6. Validation: Quantitative evaluation of a model designed to predict a particular variable. The

monitoring data would be used to test the model.

7. Compliance: Determination of the extent to which specified variables are within appropriate limits, usually in relation to government regulations; for example, fecal coliform numbers in community drinking water supplies.

Regardless of monitoring category (or other methods for determining changes in watersheds for that matter), a monitoring project should address the following important steps:

1. define clear objectives;
2. develop a plan that includes a strategy for data collection and management;
3. define personnel and budgetary constraints;
4. initiate pilot monitoring and documentation;
5. ensure full and consistent implementation of monitoring project; and
6. analyze, interpret, and report on information to ensure implementation of results.

As mentioned, the most important step is the definition of monitoring objectives and a plan (determination of variables, required sample size, etc.) before monitoring begins. Pilot monitoring is critical before the initiation of large-scale monitoring, as any changes needed to the monitoring site or methodology may preclude comparisons with earlier collected data (MacDonald et al. 1991). Once monitoring begins, regular reports are needed to clearly articulate methods, rationales, and decisions made in the monitoring program. Such information is critical in the event of staff turnover and (or) re-analysis of data/problem-solving. Documentation of whether and how a baseline was established and why certain variables were selected for monitoring is important for those interpreting results who were not part of the monitoring program.

Establishing a Baseline

Depending on the objectives of a monitoring project (i.e., type of monitoring noted above), the delineation of a baseline or reference state from which change can be quantified can be an important element of monitoring. In many cases, a baseline is not a single value, but rather a range of natural (background) variability. For example, a common misperception is that undeveloped watersheds never have turbid water; however, such streams can convey periodic high loads of fine sediment. To understand watershed variability and establish a baseline that will provide valuable insight into natural function may take many years of observation. During this data collection, most monitoring programs collect data under a reasonable amount of climatic variation, including some extremes. Hence, the baseline collection period need not be long if it contains informative data. Designing baseline monitoring projects needs to recognize the variability across the landscape. For example, some watersheds may have significant natural sediment sources, wider valley flats, and other features that make them regionally unique. Using these watersheds as baseline information sources, or extrapolating baseline data to them, is often inappropriate.

Many monitoring projects do not have the luxury of a long-term determination of baseline conditions. In some projects, this may not be critical, depending on the spatial and temporal scale of study and where estimates of baseline conditions can be derived from other variables or reasonably assumed (e.g., estimates of surface erosion from roads). If knowledge of the baseline condition is critical to a monitoring study, absence of such knowledge can result in the subjective interpretation of post-treatment responses, thereby limiting the confidence of the monitoring results in detecting change. Critically important are the selection of appropriate informative variables.

Selection of Variables

Because watershed processes are interconnected, those who make management interpretations based on monitoring results must avoid treating a process in isolation or making assumptions about linkages. For example, natural sediment production in a watershed is generally related to precipitation and snowmelt events. So although forestry practices may increase sediment production, precipitation will still be a key factor. As an example, Beak International and Aquafor Beech examined sediment accumulation in several lakes in west-central British Columbia and determined that sediment production in the watersheds was higher in the pre-logging period than during or after logging.[1] Based solely on the monitoring results, one could have concluded that logging reduced sediment production; however, these counterintuitive findings were determined to be the

1 Beak International Inc. and Aquafor Beech Ltd. 2000. Skeena Lakes operational inventory and development of sediment loading sensitivity models. B.C. Min. Environ., Lands and Parks, Smithers, B.C. Unpubl. report.

result of drier conditions during and after logging and than before logging. It is therefore essential to analyze monitoring results in the context of factors such as the amount and intensity of precipitation, timing of snowmelt, snow-water equivalent, and water yield.

Before defining and selecting monitoring variables, several questions should be considered.

- What will the variable be compared with / measured against? For example, does a standard currently exist for that variable?
- Is the variable likely to change as a result of forestry activities?
- Is there a scientific/process basis for this expectation?
- Will the change be solely associated with the disturbance, or is the expected change dependent on other factors (e.g., sediment production as related to annual precipitation)?
- How similar is the watershed in question to watersheds reported in the literature?
- What degree of sampling will be required to detect a change (e.g., sample size, sample location, and sampling frequency)?
- How and where will the variable be measured and what are the limitations to the sampling technique?
- Does the variable being measured depend on other factors and how will these factors be measured?
- How will the data (monitoring results) be used?
- Do you understand the limitations of the monitoring results?

Characteristically, monitoring is done over months to years and generally requires continued management support for resourcing. If this support is lacking, the monitoring project should be redesigned or never started (Wilford 2003).

General Limitations of Monitoring

Many challenges can be encountered when designing and implementing a monitoring program. MacDonald et al. (1991) identified the following challenges:

- a lack of information at the onset of monitoring that has implications for project design;
- difficulty in distinguishing between natural disturbance and management activities;
- difficulty in distinguishing between multiple management activities in a watershed;
- the possible time lag between an action and its effect; and
- the random nature of climatic events.

Monitoring results often depend on scale and can be altered depending on where sampling is conducted in a watershed. For example, as sampling is conducted farther away from the site of disturbance (downstream), the effects of a single disturbance will be diluted (by dilution, attenuation, and storage) and likely confounded by cumulative watershed effects. If, however, the objective is to evaluate cumulative effects, then locating sampling sites at the smallest scale may limit observations to the effect of a single activity (see Figure 4 in MacDonald 2000). Thus, the selection of sampling sites can also strongly influence the ability of a monitoring program to detect change in a watershed.

The ability to detect changes is also determined by the size of the effect (i.e., what are the limits of acceptable change), the variability in the data, the sample size, and the statistical test applied (Legg and Nagy 2006). Failure to consider these factors can limit the ability of the monitoring program to provide a conclusive answer to the question of interest. The reader is referred to Loftis et al. (2001) for further discussion on the use of statistical power in detecting changes, with and without pairing (i.e., use of an explanatory variable), and MacDonald (2000) for more information on managing and evaluating cumulative effects.

Mathematical modelling is the third method that can be used to help with both detection and prediction of change in watersheds. The purpose of many hydrologic models is to represent or simulate watershed processes (e.g., evaporation, and snow accumulation and melt, streamflow, water yield,) to predict (e.g., flood forecasting) or generate scenarios (e.g., impact analysis). In research, modelling provides the ability to study hydrologic response to disturbances on time scales that far exceed traditional field-based measurement approaches (e.g., climate change modelling). Mathematical (hydrologic) models can generate various scenarios to assess the hydrologic impacts of many different treatments before those activities are initiated. Application of hydrologic models to assist forest managers in making watershed-level decisions has been the focus of many research initiatives (e.g., Alila and Beckers 2001). Changes in water quantity, and less frequently in water quality, can also be explored. Often, results and methods can be integrated with other models (e.g., climate change models) or geographic information systems. Models can be used to investigate complex watershed management problems. Although the discussion in this section focusses on hydrologic models typically used for flow prediction, the same principles are valid for models examining other response variables (e.g., sediment, water chemistry, aquatic ecology).

Structure of Hydrologic Models

Hydrologic models represent simplifications of reality and are based on our understanding of the hydrologic processes they represent. Hydrologic models simulate the movement and storage of water within a watershed. Hydrologic models generally comprise both theoretical and empirical mathematical equations and, therefore, almost always contain parameters and variables. A variable is a characteristic of a hydrologic system that varies in space and time. Examples of variables include temperature, precipitation, and streamflow (Singh 1988). In contrast, a parameter is a value characterizing a watershed, or portion thereof, that usually remains constant over time (Singh 1988). Examples of parameters include soil and vegetation characteristics. To produce satisfactory results, model parameters must be calibrated for the watershed to which they are applied. Calibration involves adjusting model parameters so that the difference between the observed values and predicted values (model output) is minimized. Once calibrated, the model is then "validated" by evaluating its performance on a portion of data that was not used in the calibration process. The calibration and validation processes applied depend on the available data and the goals of the modelling exercise (Klemes 1986).The amount and quality of data required for calibration and validation vary with each model application. Generally, the quality of data is more important than the absolute quantity (record length). Specifically, data sets with more hydrologic variability (i.e., wet, normal, and dry years) contain more information and lead to better calibrations and predictions irrespective of record length. The selection of an appropriate model can be difficult, given the wide range in available models and the option of developing a specific model for a given watershed or question (Barnes and Bonell 2005).

Types of Models

Simulation models range from simple, regression equations to highly complex computer models that simulate the movement of water through the landscape. Models can be implemented at a range of spatial (e.g., flow dynamics through a soil column to linked global hydrology-climate models) and temporal scales (hourly vs. daily vs. annual) (Barnes and Bonell 2005). The range of available models can be organized according to two main characteristics: (1) physico-mathematical basis for hydrologic process representation, and (2) spatial discretization (see Figure 16.1). In British Columbia, several watershed-scale hydrologic models have been applied: the Distributed Hydrology Soils Vegetation Model (DHSVM), the University of British Columbia Watershed Model (UBCWM), and the HBV-EC. See Pike (2003) and Beckers et al. (2009) for reviews of watershed-scale hydrologic models suitable for application in British Columbia.

For watershed-level hydrologic models, a popular distinction is whether the model is *lumped* or *distributed*. Lumped models typically use average values to represent various processes over an entire watershed (lumped) to obtain an overall output at the basin outlet (Rosso 1992). A lumped model does not account for the spatial variability of model

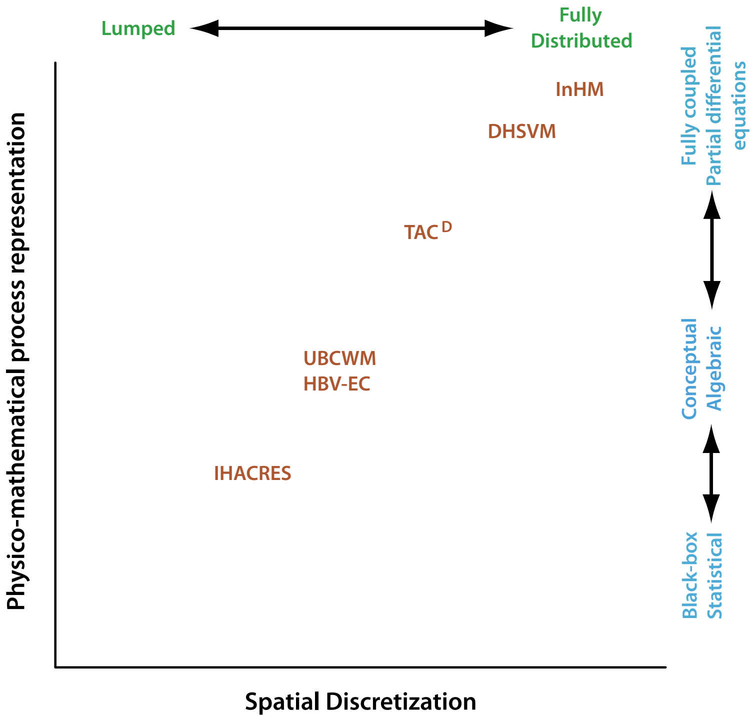

FIGURE 16.1 *Classification of common watershed models based on level of process representation and spatial discretization. DHSVM = Distributed Hydrology Soil Vegetation Model; UBCWM = University of British Columbia Watershed Model; IHACRES = Identification of Unit Hydrographs and Component Flows from Rainfall, Evaporation, and Streamflow Data; TAC^D = Tracer Aided Catchment model – distributed; InHM = Integrated Hydrology Model.*

parameters, variables, hydrologic processes, or physical characteristics within a watershed (Singh [editor] 1995). Distributed models account for the spatial variation of model parameters, variables, hydrologic processes, and geometric characteristics over the modelled watershed (Rosso 1992; Singh [editor] 1995). Distributed models typically require more information and usually contain more parameters than lumped models (Singh [editor] 1995). Distributed models usually divide a drainage basin into units or pixels of a defined size. For each of these units, a unique set of variables and parameters is assigned and maintained throughout the simulation. Data limitations, however, often prevent the realization of fully distributed models because certain system characteristics may have to be lumped within many of these models. As with the selection of appropriate research and monitoring strategies, the selection of any hydrologic model depends on objectives and the availability of data to drive the model (Barnes and Bonell 2005; Beckers et al. 2009).

Hydrologic Modelling Limitations

With the advances in computer technology, hydrologic modelling has become a popular approach to determining watershed changes. Nevertheless, more advanced models have not necessarily improved predictions of the effects of forest management on hydrologic processes or watershed response to disturbance (Beven 2001). Numerous summaries of physically based models and (or) their usefulness in predicting the potential impacts of proposed forest development have been completed (Singh [editor] 1995; Brooks et al. 1997; Pike 1998; Beckers et al. 2009). To date, few physically based models have been used in practice (forest operations) in British Columbia and are primarily research based, taking advantage of extensive data sets compiled from experimental watersheds. In addition, the models have not been tested for their ability to accurately predict the effects of forest management. (See the excellent discussion by Klemes 1986 on how models should be tested for operational application.) The most rigorous approach would be to evaluate whether a model can reproduce the treatment effect estimated from a paired-catchment experiment. Waichler et al. (2005) is one of the few examples of this approach; they compared DHSVM predictions of logging effects at the H.J. Andrews Forest in the Oregon Cascades to those estimated by pre-harvest regression.

Traditionally, hydrologic simulation models have not been widely used in forest management for reasons that include model complexity, lack of suitable data, user unfriendliness, and considerable time consumption and (or) cost. This lack of use (or trust) may partly stem from a misunderstanding of the difference between models that predict and models that generate scenarios, and the important difference in confidence in the information these models provide.

Making inferences from models can depend on the calibration and validation process used (Beven 2001). Model calibration can present a significant barrier to operational model applications when few or no watershed-specific data are available. An important limitation to some model applications is the sparse network of climate and hydrometric stations in British Columbia, particularly at high elevations. Klemes (1986) provides a series of protocols for model calibration and validation that are a function of the desired model application. Unfortunately, most models are calibrated using only precipitation and streamflow data. Although good fits between measured and predicted streamflow are possible, the need to adjust model parameters to obtain these results may produce parameter values that do not represent physical reality (Beven 2001; Seibert and McDonnell 2002). Complex models with many parameters can reach the same result with different combinations of parameter values, leading to the problem of equifinality, where a number of paths lead to the same result (Beven 2001).

Regardless of these limitations, hydrologic models are valuable in assisting our ability to transfer data between basins and predict the potential effects of disturbance on forest watershed function (Newson and Calder 1989; Alila and Beckers 2001; Dunne 2001); however, current models will continue to require a steady supply of high-quality field data (Beven 2001). Recent initiatives, such as PUB (Predictions in Ungauged Basins), are attempting to shift the prediction of streamflow, sediment, and water-quality variables from calibration-based to new, understanding-based methods (Sivapalan et al. 2003). This international initiative has two goals: (1) to improve the predictive ability of hydrologic models in ungauged basins through appropriate measures of predictive uncertainty; and (2) to develop new models and approaches that capture the space–time variability of hydrologic processes for making predictions in ungauged basins, with a major reduction in predictive uncertainty.

Until such models are developed, problems inherent in the common approach of calibrating a model solely on streamflow outputs from a basin will remain a significant barrier to improved prediction ability (Seibert and McDonnell 2002; Kirchner 2006). Depending on the parameterization and calibration process, the model may give a good fit to the calibration data with parameters that do not make physical sense (Beven 2001; Seibert and McDonnell 2002). This makes it difficult to apply the model outside the calibrated watershed or under changing conditions such as harvesting disturbance. Newer techniques espoused by Seibert and McDonnell (2002) provide a method of using data and experience to develop multi-criteria calibrations beyond simply streamflow. This approach may lead to model fits that are potentially poorer than single-criteria calibrations, but with more physical meaning and an improved ability to be used between basins (Seibert and McDonnell 2002). In many hydrologic modelling applications, data and process understanding should drive model structures—to get the right answers for the right reasons (Kirchner 2006).

The improved ability of models to predict the effects of forest management on watershed function lies in the ability of conceptualizations applied across the landscape to accurately represent key processes, and that spatially distributed data (especially precipitation and soil moisture) will be available to parameterize and calibrate models (Beven 2001). Ultimately, the objectives of the study or research question should drive the selection of an appropriate hydrologic model for a given application (Jakeman et al. 2006).

A key role of forest hydrologists and geomorphologists in British Columbia is to conduct watershed assessments identifying the total effect of past land use and natural disturbance events (e.g., mass movements, windthrow, fire, insects, disease) and projecting the potential effects of future forest development and natural disturbance. At the watershed level, rate of harvest, percent roaded area, number of stream crossings, and proportion of a watershed previously harvested can define important thresholds to indicate where further analysis may be needed before additional forest development proceeds. Watershed assessment is the evaluation of a watershed's (or watershed components') current functioning condition and likely future state.

Over the last 20 years, numerous assessment procedures have been developed. Key issues that have driven the development of these procedures include changes in the frequency and magnitude of peak flows, changes in erosion and sediment yield, changes in channel morphology and aquatic ecosystems, existing and potential cumulative watershed effects, environmental impact assessments, and the requirement for scientific input in evaluating proposed forest development. The intent of many assessment methods is to use an integrated approach that puts the individual pieces together to understand the overall interactions between "…forest practices, landscapes, natural disturbance regimes and resultant effects" (Reiter and Beschta 1995:160). Several authors have summarized cumulative effects approaches used in the United States (e.g., Reid 1993; Reiter and Beschta 1995; Berg et al. 1996) and in British Columbia (e.g., Chatwin 2001). The following section summarizes some watershed assessment approaches used in the Pacific Northwest. The following descriptions are neither comprehensive nor exhaustive, but serve as background and highlight references where further information can be sought.

Although watershed assessment approaches vary greatly, many have the following similar steps (Montgomery et al. 1995; MacDonald 2000; Ice and Reiter 2003):

1. *Scoping:* determine the issues, define the watershed area and sub-units, identify the stakeholders and beneficial uses, identify available data.
2. *Watershed assessment*: apply technical modules. This will usually involve GIS analysis, fieldwork, and professional judgement.
3. *Synthesis:* summarize and integrate the key findings from the modules.
4. *Management solutions:* recommend alternative and mitigation strategies that natural-resource managers can apply.
5. *Adaptive management:* a continuous process of monitoring watershed conditions, evaluating the performance of the plan, and advising natural-resource managers.

Watershed Assessment in British Columbia

Before the mid-1970s in British Columbia, no published watershed assessment methodology was available to hydrologists. Typically, hydrologists would discuss watershed issues with their clients, examine maps and aerial photographs, drive as many roads as possible, and explain the state of the "health of a watershed" in a brief report. The issues that prompted the assessment would vary by watershed, but typically would include effects of forest harvesting on water quality, peak flows (floods), stability of inhabited alluvial fans, and fish habitat. Within any watershed, the assessment would document sediment sources, landslides, channel alterations by logging equipment, extent of past and proposed harvesting, status of regeneration on logged areas, channel diversions, and the effects of streamside logging. These effects might be further projected to downstream areas of interest. Over the years, watershed assessment procedures applied in British Columbia evolved from threshold methods, to expert systems, to indicators, to professional judgement approaches (Chatwin 2001). This evolution follows the increase in the number of professionals available to undertake watershed assessments, the increased development and use of terrain stability mapping throughout the province, the increased use of GIS technology, and the further development of assessment procedures.

Threshold methods

A threshold approach to watershed assessment is based on the notion that watershed function will be affected if management activities such as forest harvesting exceed a prescribed threshold (usually expressed as a percentage of the watershed's total area) over a specified time period. In the threshold approach, the risk of affecting watershed function (through initiating adverse cumulative watershed effects) greatly increases as the threshold is approached or exceeded (see Cobourn 1989). If a watershed is close to its threshold, the potential for initiating adverse cumulative watershed effects can be reduced by limiting the size, shape, and location of land-disturbing activities and limiting management activities on sensitive areas (Cobourn 1989). An early example of a threshold approach used in British Columbia was to establish a harvest threshold of 33% within 25 years (see Toews and Wilford 1978). This method was presented as a planning guide that could be increased or decreased based on the specific features in a watershed.

Over a decade later, the critical threshold approach was refined with the introduction of the Equivalent Clearcut Area (ECA) concept in British Columbia. This concept was originally developed in the United States to predict the effects of roads and forest harvesting on water yield (U.S. Department of Agriculture Forest Service 1974). The ECA concept, as applied in British Columbia, established a percentage of the amount of harvesting that could occur in a watershed over a defined period of time, but gave credit for re-growth/regeneration occurring in the watershed. Although ECA was desirable to many managers because of its simplicity, many hydrologists expressed concern that the threshold approaches did not adequately recognize the variability in watershed response to forest harvesting. Also, the primary focus seemed to be on effecting changes in peak flows instead of examining the potential for riparian, fish/aquatic habitat, sediment/landslide, and channel stability impacts (Chatwin 2001).

Expert systems

Expert systems are designed to mimic the way specialists arrive at decisions, and can be considered a branch of artificial intelligence that can function as "experts" to make decisions (Hushon 1990). Characteristically, answers to questions lead users through a decision tree. The result is more than the simple addition of answer scores, because certain questions can be given greater weight and other questions (parts of the decision tree) can be minimized or even discounted. The *Watershed Workbook: Forest Hydrology Sensitivity Analysis for Coastal British Columbia Watersheds* (Wilford 1987) is an example of an expert system designed for use by forest practitioners to identify watersheds requiring further professional assessment. In the workbook, ECA thresholds are part of the basic assessment procedure, but the potential for cumulative effects is based on a broader assessment that also includes landslides, roads, and proposed harvesting.

CWAP and IWAP—1995 indicator approaches

The *Forest Practices Code of British Columbia Act* in 1995 required watershed assessments in community watersheds, watersheds with high/sensitive fish values, and other watersheds as directed by the local District Manager of the B.C. Ministry of Forests.

Two Forest Practices Code guidebooks provide guidance for watershed assessment (B.C. Ministry of Forests and B.C. Ministry of Environment 1995a, 1995b) and detail the watershed assessment procedure for the Coast (CWAP) and Interior (IWAP) of British Columbia. The first versions of these procedures (1995) were examples "of an indicator approach, which used point scores of measured watershed characteristics or land-use patterns to score the overall health or impacts of harvesting on watersheds" (Chatwin 2001:20). The selected indicators were meant to be proxies for watershed health. The 1995 procedures outlined three successive levels of analysis.

1. Level 1: A GIS-based screening procedure based on indicators of watershed impact (health).
2. Level 2: A channel stability assessment, triggered by a moderate or high level-1 score.
3. Level 3: A detailed field assessment of mass wasting, erosion, riparian condition, and stream channel stability, triggered by a moderate or high score in level 2.

The completion of a level 1 assessment produced scores for categories related to: (1) peak flow, (2) sediment, (3) landslides, and (4) riparian condition. A level-2 field assessment would be triggered if the scores for the level-1 analysis exceeded a threshold. Similarly, the level-3 assessment would be triggered by moderate to high scores in the level 2 analysis.

The indicator approach provides a consistent method for screening and identifying watersheds with and without potential forest management issues. The use of an office-based, GIS procedure in level 1 facilitated the analysis of many more watersheds than if these were investigated in the field and allowed for the focussed use of professional resources on problem watersheds (Chatwin 2001).

The approach was criticized for taking too long to complete and for misuse by those applying the procedure (i.e., interpreting indicators as goals vs. flags for further investigation, or not initiating level-2 analysis and basing management recommendations only on level-1 results) (Chatwin 2001). As a result of these issues and research summarized in Toews and Chatwin (editors, 2001), the procedure was revised in 1999 and shifted to a professional judgement approach.

CWAP and IWAP—1999 professional assessment approaches

In 1999, the British Columbia watershed assessment procedure was redefined as "…an analytical procedure to help forest managers understand the type and extent of current water-related problems that may exist in a watershed, and to recognize the possible hydrologic implications of proposed forestry-related development or restoration in that watershed" (B.C. Ministry of Forests 2001).

The 1999 version of the watershed assessment procedure differed from its predecessor in many ways. The iterative 1995 assessment procedure was replaced with a single field assessment conducted by a qualified professional with experience in forest hydrology, geomorphology, terrain stability, and forest management. The professional was required to complete a watershed report card, which paralleled the data inputs in the previous (1995) level-1 analysis (Chatwin 2001). Also different, watershed advisory committees were established to provide specific watershed information and develop recommendations for proposed forest development based on the professional's report. Committee representatives typically included forest licensees, government agencies, and the water licensee (if applicable). Additional members were added if warranted (i.e., local government and other non-government representatives).

The information collected under the 1999 procedure was viewed as more reliable because it was gathered and analyzed by a professional and it specifically pertained to the watershed under analysis (Chatwin 2001). The one-stage process was also viewed as an improvement over the iterative indicator approach; however, because of fewer controls and the considerable latitude given to professionals, a potential for bias existed in the analysis. In addition, the newer procedure was more costly than the former level-1 analysis, particularly in watersheds with no problems (Chatwin 2001).

Since 2004, the legislation requiring watershed assessments has been superseded by the *Forest and Range Practices Act*, where the decision to conduct watershed assessments is left to the discretion of the forest licensee. In most cases, watershed assessments conducted under the new legislation continue to use the 1999 procedure as a general guide, modified to suit local conditions.

United States Watershed Assessment Approaches

Several approaches to watershed assessment and analysis have been developed and applied in the United States.[2] Watershed assessments were originally developed to estimate cumulative effects and were widely applied to forest watersheds in the northern Rocky Mountains and northwestern United States. These assessment methods were created for a wide range of land uses and stakeholders, yet most have similar steps including issue scoping, watershed condition analysis, and synthesis of information. Although the steps are often similar, how the assessments are used varies. For example, assessment information was used to develop specific management practices as well as provide a broad screening tool to prioritize restoration projects and develop monitoring plans.

A complete description of these different approaches is beyond the scope of this chapter. Table 16.3 and the following discussions briefly summarize the methods and provide references for further reading. Methods discussed include Washington Watershed Analysis, *Oregon Watershed Assessment Manual*, Idaho Cumulative Watershed Effects Procedure, Forest Ecosystem Management Assessment Team (FEMAT) Watershed Analysis, Equivalent Clearcut or Road Area Models, WATSED, and North Coast Watershed Assessment Program Method. Additional details on many of these can be found in Ice and Reiter (2003).

2 A comprehensive list can be found at: http://cwam.ucdavis.edu/manuals_approaches.htm.

TABLE 16.3 *Watershed assessment approaches in the United States*

Watershed assessment method	**Type of assessment**	**Reference(s)**
Washington Watershed Analysis	Inventory and assessment leading to watershed-specific rules	Washington Forest Practices Board 1997
Oregon Watershed Assessment Manual	Screening tool to help prioritize restoration activities	Watershed Professionals Network 1999
Idaho Cumulative Watershed Effects Procedure	Quick but limited version of the Washington Watershed Analysis method	Idaho Department of Lands 2000
FEMAT Watershed Analysis Approach	Broad assessment tool for federal forest lands	Federal Ecosystem Management Assessment Team 1994; Regional Ecosystem Office 1995
Equivalent Clearcut Area, Equivalent Roaded Area, R-1	One-dimensional, easy to apply using thresholds of concern	Reid 1993; Ager and Clifton 2005
North Coast Watershed Assessment Program	Broad assessment tool focussed on anadromous fish habitat	Bleier et al. 2003
WATSED	Erosion and sediment delivery model	U.S. Department of Agriculture Forest Service 1990

Washington Watershed Analysis

The Washington Watershed Analysis (WWA), adopted in 1992, was the first watershed assessment method in the Pacific Northwest region of the United States. Based on biological and physical inventories of watershed conditions (Washington Forest Practices Board 1997), it is a collaborative process involving resource scientists and managers. Through field surveys, aerial photographs, data collection, and analysis, the effects of past management activities are used to predict watershed responses to future changes in wood, water, and sediment delivery.

The WWA method is designed to provide watershed-specific forest practice rules to protect beneficial uses of water. Key elements include: an extensive technical manual; training and credential requirements for analysts; the use of situation syntax to route impacts to specific resources of concern; development of solutions by managers; and rewards for conducting an analysis (e.g., faster approval for forest practice applications). The strengths of the method include a fairly repeatable and objective assessment process and spatially explicit watershed information. The main limitation of the procedure is the lengthy prescription-writing process, which produces prescriptions similar to standard rules (Collins and Pess 1997). In addition, landowners became reluctant to invest in this analysis method when federal agencies were unwilling to accept results for Total Maximum Daily Load (TMDL; see below) assessments or endangered species plans. The use of this method has greatly diminished in Washington State since the development of the Forest and Fish Agreement in 1999, which incorporated many of the management prescriptions into the rules.

Oregon Watershed Assessment Process

In contrast to the Washington method, which relied on experts, the Oregon Watershed Assessment Process (OWAP) was designed to be conducted by Watershed Council volunteers with limited help from technical experts. The OWAP provides a broad-scale assessment of watershed condition including all land uses. This assessment is used to prioritize restoration activities and to develop monitoring plans. Steps include: start-up and identification of watershed issues; determination of historic conditions; classification of channel habitat; assessments of hydrology, water use, riparian/wetland condition, sediment sources, channel modifications, water quality, fish, and fish habitat; and an assessment of overall watershed condition. Critical questions in each of the watershed assessment modules help the user identify how natural processes and various human activities affect fish habitat and water quality. This method offers a useful screening tool for watershed condition, but its general nature does not allow it to specifically link land use conditions to aquatic impacts.

Idaho Cumulative Watershed Effects Procedure

The Idaho Cumulative Watershed Effects Procedure (ICWEP) is intended to detect the presence of adverse watershed or stream conditions, to identify the causes of those conditions, and to identify actions that will correct and prevent existing and potential future problems. The procedure was designed to be a streamlined version of the WWA to allow more assessments throughout the state. Modules are provided for erosion and mass wasting, canopy closure/stream temperature, hydrology, sediment delivery, channel stability, beneficial use assessment, nutrients, and adverse condition assessment. A module to determine when more detailed assessments are required is also included. Although it looks at several watershed parameters, this procedure is most informative for sediment and temperature. The process also includes a re-assessment every 5 years to allow for state-wide monitoring. Because the ICWEP includes findings from a state-wide beneficial use assessment,[3] forestry is tied into other land use activities and their impacts. If data indicate that beneficial uses are not supported in the streams of an assessed watershed, then other human activities in the watershed will require evaluation. The ICWEP specifically mentions mining, grazing, overfishing, fish migration barriers, and even natural conditions.

Federal Watershed Analysis

The Federal Watershed Analysis (FWA) approach was developed for the Forest Ecosystem Management Assessment Team (FEMAT) for use on federal lands to address issues related to the Northwest Forest Plan and to design management recommendations to address those issues. The FWA is similar to the OWAP in that it was designed to "…provide a systematic way to understand and organize ecosystem information" but not to develop specific management prescriptions (although these should follow logically from the analysis). Like the WWA, experts focus on the core issues of hydrology, erosion, vegetation, stream channels, water quality, species and habitat (both terrestrial and aquatic), and human uses. Key steps include: characterization of the watershed, identification of key questions, description of current conditions, description of reference conditions, synthesis and interpretation of information, and development of recommendations.

The main strength of this approach is its coverage of terrestrial and socio-economic issues not generally addressed by other assessments (Oregon Department of Forestry 2004). One criticism of the FWA approach was that although designed to fine-tune regional watershed management prescriptions, this has not occurred regularly. The approach can also be expensive, and harvest levels on federal lands are low. Reeves et al. (2006), citing Baker et al. (2006), reported that the FWA has been applied to about 500 watersheds, though the quality and effectiveness of these assessments varied widely. They found that "the watershed analysis process should be re-examined so that it is conducted more efficiently and considers the appropriate spatial scales, including the watershed of interest, and its context within the larger basin."

Equivalent Clearcut Area and Equivalent Roaded Area methods

Several methods developed by the U.S. Department of Agriculture Forest Service are designed to assess how different forest conditions can be equated to either a clearcut (ECA) (King 1989) or a road (ERA) (Menning et al. 1997). MacDonald (2000) noted that "the idea is that all management activities can be converted to the amount of disturbance represented by a unit clearcut or unit road area…". To guide management, both methods use a threshold of concern beyond which impacts are considered unacceptable. Recovery from disturbance occurs with time. These methods are relatively simple to apply and have even been computerized (Ager and Clifton 2005); however, ECA and ERA tend to be one-dimensional, primarily addressing changes in flow or sediment, although it is usually not clear which specific water quality or resource issues are being addressed. The methods may not be capable of addressing site-specific conditions (such as position of harvest or road) or the best management practices and mitigation measures that could reduce impacts. This is especially true when the water quality concerns involve temperature, sediment, nutrients, or other water quality or aquatic habitat issues rather than flow. Although widely used in interior western and California national forests, these methods are highly lumped and empirical in treatment of impacts and are generally not considered validated. See MacDon-

3 Beneficial Use Reconnaissance Project; www.deq.idaho.gov/water/data_reports/surface_water/monitoring/overview.cfm#beneficial

ald (2000) for a detailed discussion of the ECA and ERA methods and a list of further references.

North Coast Watershed Assessment Program method
The North Coast Watershed Assessment Program (NCWAP) method was designed to develop baseline information about watershed conditions, guide watershed restoration programs and other incentive programs, and improve implementation of laws requiring watershed assessments such as the *California Forest Practices Act* and the federal *Clean Water Act*. It provided an inventory of watershed conditions and assessments of current and historic condition of the stream and watershed, with a focus on anadromous fish habitat. Stream condition was assessed using mostly professional judgements about essential habitat requirements. Road and upland conditions were assessed relative to the hazards created for watershed impacts.

The NCWAP[4] process included a range of methods to collect and analyze information. Advantages of this method included the flexibility of the approach as well as its framework for peer review; however, the method included numerous theoretical relationships whose usefulness and predictive capabilities were not field tested. This comprehensive watershed condition assessment procedure has been abandoned, probably because it could not clearly link the numerous component parts into a cogent conclusion.

WATSED
The U.S. Department of Agriculture Forest Service Region 1 and Region 4 sediment yield prediction model (WATSED) is commonly applied to watershed assessments in those regions (Ryan and Elliot 2005). WATSED is based on locally derived empirical streamflow and sediment yield data, and uses stand properties and landscape units defined by landform, lithology, and soil characteristics. Onsite surface and mass erosion estimates are adjusted for slope delivery based on topographic conditions; downstream sediment delivery is adjusted on the basis of a watershed sediment delivery ratio. The model is sensitive to alternative forest cutting and soil disturbance activities, including silvicultural practices, alternative road construction practices, and wildfire. This basic model has been modified for local applications (e.g., NEZSED and BOISED) using consensus findings from agency experts (Elliot et al. 1998). The WATSED is also a basis for surface erosion procedures in the WWA (Ryan and Elliot 2005). Although this family of models is well calibrated for the national forests where it has been applied, its reliance on local empirical results restricts transferability to other regions without careful treatment (Ryan and Elliot 2005).

Total Maximum Daily Loads
In the United States, the federal *Clean Water Act* is driving many more focussed watershed assessment methods. Under this Act, streams identified as not achieving appropriate beneficial uses and meeting water quality standards are subject to Total Maximum Daily Load (TMDL)[5] assessments.

These assessments are designed to identify the pollution loads in a watershed for a specific water quality parameter so that load allocations and other controls can be developed to achieve beneficial uses. For forest lands, this has included assessments of water quality issues such as stream temperature (Oregon Department of Environmental Quality 2002), nutrient loads (Degenhardt and Ice 1996), and sediment. Since nearly 35 000 waterbodies are impaired in the United States, significant developments in modelling are required, as well as research, to better understand which water quality standards are achievable and biologically relevant (Ice et al. 2004).

The U.S. Environmental Protection Agency (EPA) has promoted Better Assessment Science Integrating Point and Non-point Sources (BASINS)[6] to assist in TMDL assessments. This tool is "a multi-purpose environmental analysis system that integrates a geographical information system, national watershed data, and state-of-the-art environmental assessment and modelling tools into one convenient package." BASINS offers some very useful assessment components, but has limitations when applied to forest conditions. Another information source is the EPA *Handbook for Developing Watershed Plans to Restore and Protect Our Waters* (U.S. Environmental Protection Agency 2008). Additional guidance for conducting TMDL assessments for specific water quality issues is provided by the EPA[7] for sediment, nutrients, and pathogens, as well as pollution trading[8] and other considerations.

4 See www.ncwap.ca.gov/
5 See www.epa.gov/owow/tmdl/
6 See www.epa.gov/OST/BASINS/
7 See www.epa.gov/owow/tmdl/techsupp.html
8 Controlling water pollution from one source to offset impacts from another source in a manner that achieves equal or greater water quality improvements in a less costly manner.

Challenges of Watershed Assessment

In all jurisdictions where watershed assessments have been used, a common challenge is to strike a balance between addressing complex processes and conducting assessments in a timely and cost-effective manner. This challenge is particularly relevant in British Columbia, since two-thirds of the province is publicly owned forest (i.e., 60 million ha). The varied assessment methods developed over the past 20–30 years indicate that no approaches can be easily applied to assess or predict the cumulative effects of forest management (MacDonald 2000). Many of these approaches apply a rule-of-thumb or thresholds to evaluate the risk of forest management activities. Most assessments rely heavily on empirical relationships and (or) professional judgements. This is almost inevitable, given the complexity of forest management effects, watershed heterogeneity, the difficulty of routing and interacting effects, and the general lack of watershed-specific data.

SUMMARY

The ability of hydrologists and geomorphologists to make broad inferences and draw conclusions is a function of the questions asked and the approaches used to find answers. Although understanding physical processes and watershed functions in a local environment is useful, planning and management take place over the landscape. Professionals therefore need the ability to extend local data to wider spatial and longer temporal scales to answer the types of questions that managers ask (Pearce 1998). Primary constraints on the applicability of current data to answer these questions include an inability to transfer knowledge between basins and regions (Dunne 2001) and to translate data between scales (Blöschl and Sivapalan 1995). Our limitations in making inferences are also related to our ability to predict the effects of harvesting (Bosch and Hewlett 1982; Swanson 1982). If general approximations are sufficient, then we may already possess the necessary knowledge. Fundamental to detecting and predicting changes in watersheds is an understanding of how disturbances affect individual watershed processes and characteristics over time. A key consideration in detecting and predicting changes is the definition of questions of interest that will lead to the selection of the appropriate method(s) to find the answer.

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CHAPTER 17

Watershed Measurement Methods and Data Limitations

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Introduction – Measurement Methods and Limitations

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MEASUREMENT METHODS AND LIMITATIONS

Knowledge of watershed measurement methods and the respective data limitations are an important part of accurately determining changes in watersheds (Chapter 16, "Detecting and Predicting Changes in Watersheds"). Measurements provide a means to investigate important management questions and often are the only way to develop information at a local level. A common objective in the use of all watershed measurement methods is to minimize the level of error by selecting and using the most appropriate measure. Hence, a review of the required accuracy, available resources (costs), and the spatial and temporal scales of interest before embarking on sampling program is necessary. Supporting the knowledgeable use of all watershed measures is a well-planned data management system that ensures the collected data are reliable, traceable, accessible, and secure.

This chapter provides an overview of commonly used forest hydrology measurements, focussing on the limitations of both the variables measured and the measurement methods. The various section authors provide an overview of different measurement methods and common limitations and cautions for the application/interpretation of collected data (e.g., statistical, common mistakes). For each variable, a short introduction is provided but related physical processes and hydrological linkages are detailed in other chapters. The objective is to increase the reader's knowledge of the different measures available and potential issues with each measure that might lead to application errors. Each section also highlights several key publications for further information.

Measurement Scale

Common to all measurements is an acknowledgement of scale and issues related to the accuracy and error of measurement. A well-established literature exists on sampling theory (e.g., Thompson 2002), particularly in regard to statistically sound sampling schemes. In forest hydrology, however, an even greater concern is to match the temporal and spatial scales of measurements with those of the phenomenon of interest. Mismatches are often unavoidable. For example, precipitation input into a several square-kilometre watershed is often measured with a single precipitation gauge covering an area of square centimetres. In general, the spatial variability of certain phenomenon is either integrated (streamflow measurements of a watershed) or not adequately resolved since only some point data are available. Blöschl and Sivapalan (1995) provided some basic considerations on the spatial and temporal dimensions of measurements using three scales—the spacing (distance between measurements), extent (total area or volume sampled), and support (spatial representativeness of individual measurements)—termed the "scale triplet." Ideally, the scale of measurement should resolve all the variability that influences the features in which we are interested; however, logistical constraints generally impede measurements so that the full natural variability is rarely captured. For example, if the spacing of the data is too large, the small-scale variability is not captured. If the extent of the data is too small, the large-scale variability is not captured and will translate into a trend in the data. If the support is too large, most of the variability is smoothed out (Blöschl and Sivapalan 1995).

Data Recording and Accuracy of Measurements

In addition to introducing error and uncertainty through poor sampling design, measurement accuracy itself can introduce measurement error. The most common way of recording data is to deploy a data logger that electronically stores output from one or several sensors. Data loggers can collect large quantities of data with high resolution; however, the accuracy of these data may be much less than the resolution at which measurement took place. This section briefly reviews sources of error, assesses sensors typically used in monitoring programs, and recommends reporting increments for the measurements (for more details, see Spittlehouse 1986). It is based on material in Gill and Hexter (1972) and Fritschen and Gay (1979), as well as various data-logger manuals and sensor specification sheets. Measurements can be described in terms of four conditions: (1) error, (2) resolution, (3) repeatability, and (4) accuracy. These conditions affect the reporting increment, or significant digits, for the measurement. Within the current publication, the term "precision" is equated with repeatability.

1. Error of an instrument is the difference between the indicated value and the true value of the signal. It is composed of systematic and random components. A systematic error (or bias) does not change between repeated measurements. It is equal to the difference between the true value and the mean of many measurements. An example would be a constant voltage offset. Random errors vary between measurements. These errors result from electrical noise, fluctuations in temperature, and operator error.
2. Resolution of an instrument is the smallest change in the environment that causes a detectable change in the instrument. For example, if the data logger has a resolution of 1 microvolt (μV), the resolution for a thermocouple with a resolution of 40 μV/°C is 1/40 = 0.025°C.
3. Repeatability is the closeness of agreement among a number of consecutive measurements for the same value of the input under the same operating conditions. High repeatability does not necessarily imply high accuracy.
4. Accuracy of an instrument is the degree to which it will measure a variable at an accepted standard or true value. (The term "accuracy" is usually measured in terms of inaccuracy but expressed as accuracy.) In the above example, the data logger may resolve 1 μV, but the stability of its reference voltage may be accurate to only ±2 μV. Thus, the thermocouple measurement is only good to ±0.05°C. The accuracy of the thermocouple calibration is considered below.

Reporting increment or significant figures are the smallest unit of measurement that should be used in reporting the data. It is a summation of the accuracy of all parts of the sampling and measurement process.

Many factors can result in measurement error. The following factors must be considered when determining the reporting increment.

- Data logger measurement circuitry: quality of components, stability of reference voltage.
- Programming of the data logger: using the correct program and measurement range.
- Sampling interval: averaging over an hour, rather than spot-reading at the end of the hour (depends on the variability and integration of a variable).
- Sensor and cables: accuracy of calibration and maintenance of the calibration, condition, and quality of the wiring between the sensor and the logger.
- Exposure of sensor: avoiding shade on a pyranometer, shielding temperature and humidity sensors, and placing the sensors at the appropriate location.
- Replication: accounting for variation within the monitored area.

Some of the above sources of error are larger than others and their importance will depend on the measurement. For example, sensor accuracy is usually less than that of the data logger. The thermocouple noted above can be used as a hypothetical example to illustrate the various errors. The analysis is somewhat simplified. The error depends on the electronic, mechanical, and mathematical transformations in the measurement system. Differences, ratios, and non-linear transformations are all treated differently. Refer to Fritschen and Gay (1979) for more detail.

A measurement accuracy of ±2 μV (±2.5 V range) will be assumed for the logger, equivalent to ±0.05° C for the thermocouple. If the ±2.5 V range had been programmed, then accuracy would have been ±2 μV and ±0.05° C for the data logger and thermocouple, respectively. The thermocouple resolution has an uncertainty of ±5% (i.e., an accuracy of ±0.05° C), and it is connected to a reference temperature that is also accurate to ±0.1° C. Consequently, the reading on the panel of the data logger or on the computer screen has an absolute error that is the sum of the three errors: 0.05 + 0.05 + 0.1 = ±0.2° C. (In this case a linear model can be assumed.) This is a worst-case situation. The probable error assumes that errors in the different parts of the measurement system will tend to compensate for each other. It is approximately two-thirds the size of the absolute error. We will continue to be conservative and use the absolute error of ±0.2° C. Thus, the reporting increment for the thermocouple based on instrument errors is 10ths of a degree, and temperature should be rounded to the nearest 0.2° C. Non-instrument errors are more difficult to determine. Past experience is the best guide, such as knowing the variability in space and in time. For example, a shorter scanning interval is required to obtain a reliable half-hourly average of surface temperature as opposed to that required for the 10 cm soil temperature (1 s and 1 min, respectively). Similarly, more spatial replication is required for the surface temperature.

Table 17.1 presents data on sensors typically used in climate stations and hydrological studies. Sensor accuracy will vary with age and amount of use the sensor has had since the last time it was serviced and calibrated. Accuracy is often expressed as a percentage of the reading rather than as an absolute value, and this may vary with the measurement range. The accuracies quoted in the table assume that the measurement system is well maintained and sensors correctly calibrated. If this is not the case, accuracy can degrade by a factor of two or more.

TABLE 17.1 *Accuracy and reporting increment (significant figures) of typical environmental sensors monitored with data loggers (e.g., Campbell Scientific Inc.). Values are for well-maintained sensors and adequate power for the data logger.*

Variable	Significant figures	Units	Accuracy (±)	Comments
Solar radiation				Sensitivity of silicon cell can drift
hourly	xxx	W/m^2	5% or 10 W/m^2 ; whichever is greater	
daily	xx.x	MJ/m^2 per day	5% or 0.5 MJ/m^2 per day; whichever is greater	
Photosynthetically active radiation (PAR)				Opacity of filter over silicon cell changes over time
hourly	xxxx	μmol/m^2 per second	5% or 20 μmol/m^2 per second; whichever is greater	
daily	xx.x	mol/m^2 per day	5% or 1 mol/m^2 per day; whichever is greater	
Air temperature	xx.x	°C	0.2°C	Stable
Relative humidity	xx	%	3%	Polymer-based elements give increased RH over time
Vapour pressure	x.xx	kPa	0.05 kPa	
Wind speed	xx.x	m/s	< 2 m/s = 0.5 m/s > 2 m/s = 0.2 m/s	Stall speed increases with wear and age of bearings
Wind direction	xxx	°	5°	
Rainfall	xx	mm	Tipping volume (1 mm, 0.25 mm, or 0.1 mm)	Pollen, debris, and insects block inlet
Soil temperature	xx.x	°C	0.2°C	
Soil moisture block	x.xx	MPa	> −0.2 MPa = 0.05 < −0.2 MPa = 0.2	Contact poor in coarse soil, dissolve in acid soil
Soil water content	xx.x	%	2.5%	Very good contact required
Water level	x.xxx	m	0.001–0.01 m	Sediment can cover instrument
Water temperature	xx.x	°C	0.2°C	
Specific conductivity	xx.x	μS/cm	1 % or 1 μS/cm; whichever is greater	Non-linear dependence on water temperature
Turbidity	xxx	NTU	2–4% NTU	Very sensitive to fouling of sensor
Snow depth	xxx	cm	0.4% or 1 cm; whichever is greater	Sonic ranging sensor, temperature dependent

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Weather – Temperature, Humidity, Wind, Radiation, and Precipitation Measurement

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Watershed hydrology is driven by the interaction of weather conditions, surface cover, and geomorphology. The weather provides the energy and water inputs to the watershed. In turn, these control the delivery of water to the surface, loss of water by evaporation, and soil heating or cooling, and influence the type of vegetation cover through plant survival, growth, and disturbance. The water input of precipitation is a well-recognized variable; however, the energy input is often not as well understood. It is a result of the solar and longwave radiation balances and convective transport of sensible and latent heat (Male and Gray 1981; Monteith and Unsworth 1990). These terms, along with snowmelt and evaporative loss, can be quantified through measurements of incident and reflected solar radiation, longwave radiation emitted by the sky and the surface cover, air temperature, humidity, and wind speed. The following subsection describes methods (instruments and their application) for accurately measuring these variables. Subsequent subsections describe how to measure the effects of the weather on snow accumulation and melt, precipitation interception, evaporation, and soil thermal conditions.

AIR TEMPERATURE

Air temperature is the temperature indicated by a thermometer exposed to the air in a place sheltered from direct radiation (Glickman [editor] 2000). It is useful for indicating whether precipitation fell as rain, snow, or a mixture; it also influences snowmelt rate, stream temperature, and plant phenology and growth. Typical reported values are daily maximum, minimum, and mean air temperature. Temperature is often integrated over time as degree-days. There is one degree-day for each degree the mean daily temperature is above or below a base temperature. For example, growing degree-days are accumulated above a 5° C base, and heating degree-days are accumulated for temperatures below an 18° C base.

Air temperature is measured with mercury or alcohol in glass thermometers, thermocouples, thermistors, platinum resistance thermometers, and sound-based instruments. For all instruments, it is important to ensure that the sensor (thermometer, thermocouple, etc.) is at air temperature (see also subsection on Soil Thermal Regime in "Soils" section). This means that for most instruments, the sensing element must be shaded from heating by solar radiation and from precipitation while allowing ventilation. Shading is required because the temperature measurement of an exposed thermometer will depend on the colour, size, and heat capacity of the thermometer and intensity of solar radiation. Typical radiation shields include the standard Stevenson's Screen and the Gill multi-plate radiation shield. A single layer of shielding is not usually sufficient to minimize heating and many shields are double-hulled. High-accuracy monitoring systems often use artificial ventilation to keep the thermometer at air temperature. Fine wire thermocouples (< 0.2 mm diameter) and sonic anemometers do not require shielding, although these are not sensors used in routine measurements.

The standard thermometers used in the Meteorological Service of Canada network are mercury or alcohol in glass. These instruments are located in a Stevenson's Screen 1.5 m above the ground and record the maximum and minimum temperature since last read and the current temperature (Meteorological Office 1982; World Meteorological Organization 2008). A well-watered grass surface is the reference surface for weather networks around the world (World Meteorological Organization 2008). Electronic monitoring systems use thermocouple, thermistor, or platinum resistance thermometers and are often mounted in Gill multi-plate or home-made shield. These thermometers are of a different size and heat capacity than the standard glass thermometer and will give slightly different values of temperature under the same conditions. The typical measurement resolution is 0.01–0.2°C depending on thermometer and monitoring system (e.g., human eye, data logger); however, accuracy is at best 0.1°C and more likely 0.2°C with most electronic devices. Polynomial formulae are used to convert the signal from thermocouples and thermistors to temperature. It is assumed that different sensors of the same composition have the same calibration (Campbell Scientific Inc. 2002).

Manual measurements at standard weather stations are usually made at 8:00 a.m. The 8:00 a.m. reading on the maximum thermometer is assigned to the previous day and the minimum of the current day is assumed to occur just after sunrise. The daily average is calculated as the mean of the minimum and maximum temperatures for the day, and is a good approximation of the true mean obtained by integrating temperature through the day. Automatic systems usually have a daily output at midnight. Under certain weather patterns, the values for the maximum and minimum may disagree with the data from the standard weather station. Automatic systems can give a true daily average temperature by integrating the temperature over a 24-hour period.

Environmental lapse rates calculated from a network of stations are often used to interpolate or extrapolate to other elevations. These lapse rates will vary during the day, from day to day, and by season and are different for the maximum, minimum, and average temperatures. A typical value for the monthly average temperature is 0.6°C/100 m of elevation. Over a few hundred metres, vertically minimum temperature lapse rates may be negative (i.e., an inversion). Plots of daily and monthly temperature for one station versus another or group of stations in the same area can be used to check for consistency among point measurements. The relationship should be a straight line with an offset usually caused by elevation or site-specific effects. Changes in the offset usually indicate some change in the station measurement. The change should persist for 5 or more years to be considered significant because anomalous periods can occur at one station (Thom 1966).

Air Temperature Measurement Errors

The accuracy of the sensor will depend on the resolution of the measuring device, mode of operation, location errors, and observer errors. Proper shielding of the temperature sensor and location are very important for a representative temperature measurement. The shield should be well ventilated and in an area that does not have a microclimate substantially different from the conditions of interest. For example, it should not be located close to buildings because convective and radiative heat from these structures may bias the reading. A shielded thermometer over a bare area will be warmer than one over an adjacent well-watered grass surface. Even with shields, the potential exists for the thermometer to be warmer than air temperature. The specification sheet for the widely used Gill multi-plate radiation shield indicates that a wind speed of 2 m/s is required to reduce overheating to less than 0.5°C under high solar intensity (Young 1994; Erell et al. 2006). Homemade shields, such as tubes and inverted Styrofoam cups, can significantly overheat under low wind speeds (Erell et al. 2006). In addition, the surface albedo (e.g., snow cover) can lead to increased overheating from reflected radiation, particularly when the shields are not designed for shielding from the bottom.

Temperature Data Availability

Daily Canadian temperature data from the Meteorological Service of Canada (MSC) network are available for free through the MSC website (www.climate.weatheroffice.gc.ca/prods_servs/index_e.html#cdcd). Some stations are up-to-date; others are about 2 years behind. Historical monthly data for Canada that have been checked for homogeneity are also available; however, these data are not the official MSC in situ station record and therefore should not be used for legal purposes. Hourly and daily temperatures are available from the B.C. Forest Service Fire Weather Network (http://bcwildfire.ca/Weather/stations.htm), though not all stations are maintained during the winter. Interpolated 30-year normals of monthly maximum, minimum, and average temperature adjusted for elevation are available for British Columbia and adjacent areas. These data, variables such as degree-days and frost-free period, and climate change scenarios are available through stand-alone MS Windows and Web-based applications (ClimateBC; www.genetics.forestry.ubc.ca/cfcg/climate-models.html) (Spittlehouse 2006; Wang et al. 2006). Interpolations of monthly data for individual years back to 1900 are available at 10-km resolution (McKenney et al. 2006) and at 400-m resolution with ClimateBC (Mbogga et al. 2009).

Humidity refers to the water content of the air in absolute terms or relative to the saturated water content. The humidity of the air is an important weather variable controlling the rate of evaporation from vegetation, soil, and water bodies. Typical recorded values are daily maximum, minimum, and average humidity. Humidity is commonly reported as: (1) vapour pressure, (2) relative humidity, (3) dew point temperature, (4) absolute humidity, (5) mixing ratio, and (6) vapour pressure deficit. Vapour pressure (Pa, mb) is the partial pressure of water vapour in the air. The relative humidity (%) of the air is the ratio of the vapour pressure to the saturated vapour pressure at that temperature multiplied by 100; thus, the same vapour pressure produces a different relative humidity as the temperature changes. Dew point temperature (°C) is the temperature to which the air must be cooled for condensation to occur. The absolute humidity is the ratio of the mass of water vapour to the volume of air (g/m^3). The mixing ratio is the weight of water vapour in a volume of air to the weight of the air (g/g). The vapour pressure deficit (Pa, mb) is the difference between the saturated vapour pressure and the vapour pressure of the air. Saturated vapour pressure increases exponentially with temperature (List 1985; Glickman [editor] 2000).

The saturated vapour pressure is frequently described as the maximum amount of water the air can hold at the air temperature. Although convenient, this analogy is incorrect. The saturated vapour pressure at a temperature is that for which the water vapour is in equilibrium with a plane surface of water in a pure liquid or solid phase (Glickman [editor] 2000). It is a function of the kinetic energy (temperature) of the molecules of water and their evaporation from the plane surface. The saturated vapour pressure is therefore the same in air as in a vacuum, where you might expect more space for the water molecules and thus a large saturated vapour pressure. It is lower over a salt solution because of the attraction of the water molecules to the salt, and consequently increases the energy required for the molecules to evaporate (Bohren 1987). It is also lower over ice than water because the latent heat of sublimation is greater than the latent heat of evaporation.

Instruments to measure humidity include hair hygrometers, wet bulbs, polymer-based (resistive and capacitive) sensors, chilled mirror dew point hygrometers, and infrared hygrometers (Campbell Scientific Inc. 2002; World Meteorological Organization 2008). Wet-bulb and polymer-based sensors are the most common sensors used in weather station networks. The former require regular maintenance and artificial ventilation. Wet-bulb and polymer-based sensors are usually combined in the same housing as the temperature sensor and require the same shielding, ventilation, and proper location as described above for air temperature. These sensors are found in instruments for manual humidity measurement and electronic monitoring with the polymer-based sensors most commonly used in automated monitoring systems. Assmann and sling psychrometers are typical examples of instruments based on wet bulbs that have air and wet-bulb temperatures measured using glass thermometers and are read manually. These instruments are ventilated with a wind-up motor or by manually rotating them. Cotton wicks on the wet bulbs are wetted with distilled water; and after waiting a minute to reach equilibrium, the temperature of each thermometer is read. A table or an equation is used to convert the readings to humidity.

Humidity Measurement Errors

Polymer-based sensors drift over time. This is noticeable in the maximum humidity, which will indicate values above 100% and this increases over time; the minimum humidity will have drifted by a similar amount. Recalibration is therefore recommended every 2–3 years (Campbell Scientific Inc. 2002). Although measurement resolution on these sensors is frequently 0.1%, their accuracy as specified by the manufacturer is at best ±2%. The accuracy measures of humidity that depend on air temperature are subject to the errors of the temperature measurement.

Wet-bulb sensors are prone to errors if not regularly maintained. The water reservoir can dry out, the ventilating fan can fail, and in dusty environments the wicks become contaminated. These problems can lead to an overestimation of the wet-bulb temperature. Assmann and sling psychrometers should be kept out of direct sun when not in use.

Humidity Data Availability

Only a subset of the Meteorological Service of Canada (MSC) stations measure humidity. These data can be obtained through the MSC website (www.climate.weatheroffice.gc.ca/prods_servs/index_e.html#cdcd). Relative humidity data are available for British Columbia from the B.C. Forest Service Fire Weather Network (http://bcwildfire.ca/Weather/stations.htm). Humidity data can be extrapolated with elevation assuming that the vapour pressure is relatively constant with height. Local temperature data can then be used to convert to relative humidity. Another approach is to use the saturated vapour pressure at the dew point temperature. In many situations, the minimum air temperature reasonably approximates the dew point temperature (Allen et al. 1998).

WIND

Wind is the horizontal speed and direction of air movement over the ground surface. Wind measurements are required in hydrology for calculating evaporation and sublimation, evaluating the potential for blowdown of trees, and determining insect and seed dispersal. Wind speed and direction are usually reported for the mean flow in the horizontal plane (Glickman [editor] 2000; World Meteorological Organization 2008); however, the vertical component to the wind is usually only measured for specific research studies and is not considered here.

The wind speed is measured with an anemometer (m/s or knots) and is reported as the average for a period as well as the gustiness or the peak wind speed during a specific time interval. The wind moves a spinning cup or propeller that activates a mechanical or optical switch, or generates an electrical current. The angular velocity of the cup or propeller is proportional to the wind speed, although a threshold wind speed usually exists below which the rotor will not turn. This varies from 0.1 to 1 m/s, with 0.5 m/s being typical of commercially available cup anemometers. Other devices for wind speed include pitot tubes and sonic anemometers. Wind speed can be estimated manually based on the effect of the wind on moveable objects. Remote sensing of wind speed uses SODAR (i.e., sonic detection and ranging), lidar (light + radar), and radar.

Wind direction is measured with a wind vane or aerovane in degrees of the compass and specifies the azimuth from where the wind is coming (Glickman [editor] 2000; World Meteorological Organization 2008). The signal generator is usually a potentiometer that is calibrated to read from 0 to 360°. Hourly and daily wind direction must be determined with algorithms that generate a histogram and a wind rose (i.e., frequency of time in usually eight segments of the compass and the wind power for the time in each section). Measuring mean wind direction can result in misleading measurements; for example, the average of north–northwest and north–northeast is south. Counters, chart recorders, or electronic data loggers record the output from anemometers and wind vanes.

Exposure is the most important aspect of reliable wind measurement. Wind should be measured in open terrain where the distance to the nearest obstruction is at least 10 times the height of the obstruction. The ground cover will affect wind speed because of the way it absorbs momentum, thus reducing the wind speed (Monteith and Unsworth 1990). Wind may also be channelled or diverted by topography. Wind speed increases rapidly with height (logarithmic wind profile) and it is important to measure at the standard reference height (10 m), or at a known height so that wind can be converted to the reference height if the surface roughness is known (World Meteorological Organization 2008). The exposure requirements may be difficult to meet in forested watersheds. What was once a good site for wind measurement, such as a large clearcut, changes over time as the forest regrows around the anemometer and wind vane.

Sensor response of propeller and cup anemometers is faster for acceleration than deceleration, so these anemometers tend to overestimate wind speed by up to 10% (World Meteorological Organization 2008). The bearings of anemometers deteriorate over time, increasing friction and stall speed. High wind speeds may damage anemometers and wind vanes. An increase in the measured frequency of lower wind speeds over time could indicate such problems and (or) the regrowth of vegetation around the monitoring area. Anemometers and vanes are sensitive to levelling errors and to icing in winter, with problems indicated by periods when the anemometer is stalled for a long time or there is a severe distortion of the wind rose.

Wind Data Availability

Daily Canadian wind speed and direction data from the Meteorological Service of Canada network are available for free through the MSC website (www.climate.weatheroffice.gc.ca/prods_servs/index_e.html#cdcd); however, the network is sparse. Wind data are also available from the B.C. Forest Service Fire Weather Network (http://bcwildfire.ca/Weather/stations.htm).

RADIATION

Radiation is electromagnetic energy emitted as a function of the temperature and emissivity of the emitting surface. The flux of radiation to and from the Earth's surface provides energy to warm and cool the surface, to evaporate water, to melt snow, and for photosynthesis (Monteith and Unsworth 1990). Radiation in certain frequencies can have negative impacts through destructive effects on cells (L'Hirondelle and Binder 2002; Kelly et al. 2003). Two forms of radiation at the Earth's surface are of interest to hydrologists: shortwave or solar radiation (290–4000 nm) and longwave radiation (> 4000 nm). Because the Sun's surface temperature is about 6000 K, over 99.9% of the energy it emits is at wavelengths of less than 4000 nm. Solar radiation reaching the Earth's surface is composed of direct and diffuse (scattered direct) radiation. The energy emitted from surfaces on the Earth or gases and particles in the atmosphere at –40 to +60° C (longwave or terrestrial radiation) is from wavelengths longer than 4000 nm (Glickman [editor] 2000; Stoffel and Wilcox 2004). Reflected energy is the short or longwave radiation reflected by a surface and is a function of the radiative properties of that surface (Monteith and Unsworth 1990; Glickman [editor] 2000). The solar reflectivity (albedo) varies from 0.92 for fresh snow to 0.06 for a burnt (blackened) surface. The longwave reflectivity of vegetation, soil, and water is less than 0.05.

The shortwave component is measured as two separate streams: ultraviolet (UV) (280–400 nm) and global radiation (400–3000 nm). Photosynthetically active radiation (PAR) or visible radiation is a component of the latter spectrum (400–800 nm). Shortwave radiation is measured with pyranometers that are sensitive to the different frequency bands and that have different measurement units. Longwave radiation is measured with a pyrgeometer. A net pyrradiometer measures the difference between upward and downward fluxes of short- and longwave radiation (World Meteorological Organization 2008). Methods to measure or estimate direct and diffuse radiation are also available (Monteith and Unsworth 1990; Black et al. 1991; Wood et al. 2003; World Meteorological Organization 2008).

Typical recorded values of radiation are hourly and daily averages, totals, and peak intensity. Solar, longwave, and net radiation measurement units are W/m^2 (a Watt is a Joule per second) and MJ/m^2 per day. PAR, also called quantum radiation, is measured as micromoles per square metre per second ($\mu mol/m^2$ per second and mol/m^2 per day). Conversion of W/m^2 to PAR depends on the spectral distribution in the light. For daily totals above forest canopies, mol/m^2 per day = 2.04 ± 0.06 MJ/m^2 per day (Meek et al. 1984). Measurement of radiation specific to the sensitivity of the human eye is in lumens (World Meteorological Organization 2008). Instruments to measure UV radiation measure only the UV-B part of the spectrum (280–320 nm) or UV-B and UV-A (320–400 nm). Many of these instruments are constructed so that the output is weighted by the erythermal function—the sensitivity of human skin to the different UV wavelengths (World Meteorological Organization 2008).

Relatively inexpensive pyranometers use silicon diodes and filters tuned for the spectral distribution of sunlight. The spectral distribution changes when it is reflected from a surface (Monteith and Unsworth 1990) and as it passes through a vegetation canopy (Vézina and Boulter 1966; Yang et al. 1993). Consequently, the calibration of silicon-based pyranometers must be adjusted when used in these applications. Thermopile-based pyranometers can be used in all situations. Silicon sensor base PAR instruments can be used below canopies but, because of the change in spectral distribution, the conversion to solar energy is not the same as for above-canopy energy. Instruments for reliable measurement of longwave radiation and net radiation are thermopile-based.

Solar radiation can be estimated from the number of sunshine hours in a day (Hay 1979; Allen et al. 1998). It is also estimated from the daily temperature range and calculated global radiation above the Earth's atmospheres (extra-terrestrial radiation) (Bristow and Campbell 1984; Allen et al. 1998). These methods work best for summer conditions and improve with averaging over time. Calibration coefficients are usually location specific.

Measurements of solar radiation reflected from the ground surface or emitted longwave from the surface below an instrument are specific for that surface. Knowledge of the solar reflectivity (albedo) of other surfaces in the watershed allows calculation of reflected solar from the incident value. Emitted longwave radiation from other surfaces can be determined from surface temperature and emissivity. The longwave emissivity of vegetation, soil, and water is greater than 0.95 (Monteith and Unsworth 1990). Formulae are available for calculating atmospheric (downward) longwave radiation. These are based on the temperature and (or) the humidity of the air and the amount of cloud cover (Monteith and Unsworth 1990; Allen et al. 1998). Trigonometric equations are used to adjust measured or calculated solar radiation for slope and aspect (Iqbal 1983).

Radiation below forest canopies has a high spatial variability. Therefore, an array of instruments or roving instruments (Black et al. 1991; Fassnacht et al. 1994; Chen et al. 2006) is required to reliably determine the below-canopy regime. In relatively uniform canopies, daily totals at a single, carefully chosen point may give a reasonable estimate of the average below-canopy radiation environment. Hemispherical photographs and computer programs to calculate radiation penetration through canopies reliably estimate below-canopy incident solar and PAR (Frazer et al. 2000; Hardy et al. 2004). The forest and sky view factors determined from these photographs are used to calculate the longwave radiation below the canopy (Essery et al. 2008).

Radiation Measurement Errors

Instruments for reference measurements of incident radiation (downward from the sky) should be installed so that these have an unobscured view from the zenith to the horizon, although this can be difficult to achieve in mountainous terrain. It is important to at least ensure that the Sun's path is not blocked. An unobscured reading allows for correction of terrain-shading effects that will vary within a watershed (Nunez 1980; Flint and Childs 1987). Radiation instruments are usually mounted horizontally unless some specific need exists to directly determine radiation incident and emitted from angled surfaces (Szeicz 1975; Stoffel and Wilcox 2004; World Meteorological Organization 2008).

Dew, rain, frost, snow, and dirt accumulate on the surface of instruments, especially those that are upward looking. It can be difficult to determine when such contamination affects the signal from these instruments. Snow and dirt are the main problem contaminants for solar radiation instruments. Comparison of solar radiation with an instrument measuring reflected solar radiation in the open would indicate when the incident measuring instrument is obscured by snow. A curve of daily clear sky radiation for the site should be created and compared with daily total radiation. Also, the measured solar radiation cannot be higher than the extraterrestrial value of solar radiation when averaged over half an hour or more (Stoffel and Wilcox 2004). If dew, rain, snow, dirt, or frost collect on the domes protecting the sensing element, then longwave measurements will be affected because the sensors will respond to radiation at the temperature of the contaminants. It can be difficult to determine when the signal from these instruments is affected by contamination of the domes.

Sensitivity of radiation instruments is usually quite stable over many years, though some manufacturers recommend recalibration every few years. This is done by mounting a new sensor close to the old one and comparing 1- to 5-minute average values a few times during a day, preferably for a mixture of clear sky and cloudy conditions, or returning the instrument to the manufacturer.

Radiation Data Availability

Few radiation measurement sites exist in Canada and the data are not readily obtained online. More sites measure the number of sunshine hours in a day and these data can be converted to solar radiation (Hay 1979; Allen et al. 1998); however, these sites are part of a sparse network usually based in valley bottoms and the data are not up to date or readily available.

PRECIPITATION

Precipitation puts water in the watershed. Precipitation measurements help determine water availability for evaporation and streamflow, and the risk of forest fires, landslides, and soil erosion. Precipitation is liquid (rain) or frozen (sleet, hail, graupel, snow) water or a combination of both falling from the sky (Glickman [editor] 2000). Measurement of the accumulation and disappearance of frozen precipitation on the ground is discussed in the following subsection. Precipitation is measured as depth of water that would accumulate on a horizontal surface. Typical recorded values for precipitation are the daily, monthly, and annual totals (depth of water in millimetres), as well as storm total, maximum intensity (millimetres per minute or per hour), and duration (hours).

Precipitation is measured at a point using a manual or automatic recording gauge and over an area using meteorological radar (e.g., Doppler) or satellite images. Measurement of rainfall with a gauge is less prone to error than the measurement of solid precipitation because it is less susceptible to the influence of wind on "catch" by gauges. Some gauges are suitable only for measuring rainfall, and others are used only for solid precipitation. Very few can measure both forms reliably. Precipitation is usually not uniform in spatial distribution, intensity, or duration within a storm. Wind flow interacting with watershed topography also affects the distribution of precipitation (Arazi et al. 1997).

The standard technique for measuring rainfall is a plastic or metal cylinder with a sharp edge and funnel-like cover to minimize evaporation. The standard Meteorological Service of Canada (MSC) gauge is 91 mm in diameter with the orifice 305 mm above ground and no shield. These gauges either contain a cylinder graduated in millimetres of water or require pouring the water into a measuring cylinder. Rainfall is measured to the nearest 0.2 mm; an accumulation of less than this is called a "trace." If these gauges are not measured daily, then a small amount of mineral oil or kerosene is added after each measurement to cover the surface of the water and reduce evaporative loss.

The MSC measures frozen precipitation using Nipher gauges. This gauge consists of a holding cylinder (127 mm in diameter and 560 mm deep) surrounded by an inverted bell-shaped shield to reduce the effects of wind around the cylinder (Goodison et al. 1981). Snow caught in the holding cylinder is melted manually and the water equivalent determined at least daily. The water equivalent of the snowfall is also calculated from the depth of snow that has fallen on a snowboard since the last measurement multiplied by the density. A density of 100 kg/m^3 is often assumed although it can vary by up to 30% depending on the air temperature during the storm and the amount of settling that occurs before measurement (Goodison et al. 1981). Large-capacity storage gauges for snow (e.g., the Sacramento gauge) are used in remote areas. These gauges contain antifreeze to melt the snow and light oil to minimize evaporative loss. The depth of fluid is measured with a ruler.

Precipitation intensity or amount can be measured automatically using weighing gauges or tipping buckets. The latter method is usually restricted to rainfall measurement. The tipping bucket gauge has a pair of buckets that pivot under a funnel such that when one bucket fills with 0.1, 0.25, or 1 mm of rain, it tips, discharging its contents and bringing the other bucket under the funnel. Tipping activates a switch that sends a pulse to the recording device. The weighing gauges can have a clock-driven chart to record weight or send an electronic signal to a data logger from a pressure transducer. Weighing gauges used to measure snow, contain antifreeze to melt the snow. A commonly used gauge in British Columbia consists of a large standpipe with a pump to mix the antifreeze and precipitation. This reduces the chance that an ice cap or snow bridge will develop at the surface of the liquid or at the top of the gauge. Heated gauges to melt solid precipitation are available, but these are not reliable for long-term, unattended monitoring.

Manual and automatic gauges sometimes have a shield or baffles around the orifice of the gauge to reduce wind flow and improve catch (Sevruk 1985a, 1985b; Goodison et al. 1998; World Meteorological Organization 2008). Wind shielding and wind correction are particularly important for measuring solid precipitation. The best gauge location is within a clearing surrounded by trees or other objects to reduce wind, with a 45° (angle from the vertical) conical space above the gauge and no objects closer than twice (preferably four times) their height above the gauge. Gauges to measure solid precipitation should be mounted so that these are at least 1–1.5 m above the maximum snow surface (Goodison et al. 1981).

Surface condensation (e.g., dew, fog, rime, and hoar frost) requires specially designed instruments to properly record the water deposited (Monteith 1957; Goodman 1985; Schemenauer and Cereceda 1994; Glickman [editor] 2000); World Meteorological Organization 2008).

Integration over a Watershed

Integration of precipitation over a watershed is necessary for hydrological work. Areal measurement of rainfall rate with radar is based on the backscattered power of the echo returns. Typical radar has a 4-km^2 grid resolution. These data are not available over most of British Columbia.

Precipitation over a watershed is frequently estimated from a network of point measurements (National Oceanic and Atmospheric Administration 2006). One method used when a few stations are located mainly in valley bottoms is to calculate an environmental lapse rate for precipitation. However, variability in the areal range of storms, distribution of rainfall within the storm, and topographic influences mean that the lapse rates will vary by storm, season, and year. The error in this approach decreases with an increase in averaging time. In steep terrain, precipitation at lower elevations is often controlled by the adjacent upper levels of the topography, minimizing lapse rates over hundreds of metres in elevation (Daly et al. 2002).

Another simple method is to calculate the arithmetic mean of all the points in the area. The use of isohyetal analysis involves drawing estimated lines of equal precipitation amount over an area based on point measurements in a network. The magnitude and extent of the resultant areas of precipitation versus the total area in question are considered to estimate the areal precipitation value. The Thiessen polygon graphical technique weights the value for each station in the network on the basis of the relative areas represented by each station. The individual weights are multiplied by the station observation and the values are summed to obtain the areal average precipitation. The distance weighted/gridded method weights each observed point value on the basis of the distance from the grid point in question. The areal average precipitation is calculated from the sum of the individual observed station value multiplied by the station weighting and divided by the number of grid points. Index stations use predetermined station weights based on climatology to compute basin average precipitation (National Oceanic and Atmospheric Administration 2006).

Precipitation Measurement Errors

The accuracy of gauge catch has been evaluated under a wide range of climate regimes (Goodison et al. 1981, 1998; Meteorological Office 1982; Sevruk 1985a, 1985b). All point measurements are subject to error and usually underestimate precipitation. Accuracy will depend on the resolution of the measuring device, mode of operation, and location and observer errors. Assuming a correctly calibrated instrument, typical measurement resolution is 0.25 or 1 mm depending on the device. Wetting errors caused by water adhering to the funnels and walls of the gauges may also occur. Wind flow around a gauge affects the catch and can result in a significant underestimate of precipitation. This is particularly the case for snow, with over 50% underestimation in some conditions (Coulson [editor] 1991; Goodison et al. 1998). A snow cap or ice lens can develop on gauges for measuring solid precipitation if these gauges have a small orifice and (or) if the antifreeze and water mixture in the collection vessel is not well mixed. Obstructions that shield the gauge from precipitation above, or result in precipitation splashing or dripping onto the orifice, must also be avoided. Dew, fog, rime, and hoar frost can contaminate the precipitation measurement and are unlikely to be equal to the full amount deposited by these processes (Glickman [editor] 2000). Evaporation losses from manual gauges can be reduced with a small amount of mineral oil or kerosene to cover the water surface. Because tipping bucket gauges tip only when full, a small amount is usually left in an untipped bucket at the end of a storm; this water evaporates or is included in the next storm total. Many manual gauges are rarely observed at midnight; thus, the precipitation may not be assigned to the actual day it fell, or the wrong amount is assigned to a day. This is important to consider when comparing automated measurements with manually measured data because automated systems usually have a daily total determined at midnight. Automatic systems also require occasional calibration, as instrument response can change over time.

Plots of cumulative monthly or annual precipitation for one station versus another or group of stations in the same area can be used to check for consistency among point measurements. The relationship should be a straight line. Changes in slope can reflect errors in a gauge, though usually the break in slope must persist for 5 or more years to be considered significant, since one station may have anomalous years. Data from before the change in slope can be adjusted by multiplying it by the ratio of the new slope to the old slope (Thom 1966).

Precipitation Data Availability

Daily Canadian precipitation data from the Meteorological Service of Canada (MSC) network are available free through the MSC website (www.climate.weatheroffice.gc.ca/prods_servs/index_e.html#cdcd). Some stations are up-to-date; others are about 2 years behind. Historical monthly data for Canada that have been checked for homogeneity are also available. However, they are not the official MSC in situ station record and therefore should not be used for legal purposes. Hourly and daily precipitation for spring through fall is available from the B.C. Forest Service Fire Weather Network (http://bcwildfire.ca/Weather/stations.htm). Precipitation intensity data (Intensity-Duration-Frequency curves) are also available (Hogg and Carr 1985). Interpolated 30-year normals of monthly maximum, minimum, and average precipitation adjusted for elevation are available for British Columbia and adjacent areas. These data and climate change scenarios are available through stand-alone MS Windows and web-based applications (ClimateBC; www.genetics.forestry.ubc.ca/cfcg/climate-models.html) (Spittlehouse 2006; Wang et al. 2006). Interpolations of monthly data for individual years back to 1900 are available at 10-km resolution (McKenney et al. 2006) and at 400-m resolution with ClimateBC (Mbogga et al. 2009).

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Weather – Snow Measurement

RITA D. WINKLER

SNOW ACCUMULATION AND MELT

This subsection describes techniques for measuring snow on the ground, including its depth, water content, and density, and the rate at which the snowpack disappears (ablation). Typically, snow surveys are undertaken to quantify the amount of water stored in snow on the ground, melt rates, and snow cover distribution in a watershed. This information is used to predict spring runoff and flood potential, as well as to forecast water supplies. Snow information is also useful for scheduling winter logging operations, maintaining access, and predicting avalanches, as well as in silviculture, wildlife management, and recreation. Techniques for measuring solid precipitation are described in the previous subsection and snow interception by forest vegetation is discussed in the next subsection. Methods for describing snow structure, grain forms, and stability can be found in the avalanche literature (Canadian Avalanche Association 2002; McClung and Schaerer 2006).

Snow Depth

Snow depth is the height of the snowpack above a reference point (in millimetres), usually the ground surface. Although snow often appears to be uniform at its surface, the actual depth is highly variable and is affected by features on or near the ground surface such as logs, stumps, shrubs, and other roughness elements. Snow depth changes between snowfall events and over the winter, becoming more or less dense depending on the weather. Consequently, snow depth alone does not indicate the volume of water stored in the snowpack.

Individual snow depth measurements can be relatively simple to obtain. Snow depth can be measured by reading a ruler fixed at a specific point or by taking a series of ruler measurements at a site and averaging them. In deep, hard-packed, or icy snow, a hollow, extendable steel rod with a rounded solid, steel tip is used (Woo 1997). The surveyor must be certain that the ruler or rod has reached the ground but not penetrated the surface. A snowboard (a sheet of plywood, often painted white or covered with white flannel, placed level on the ground surface) is commonly used as "ground" or a consistent reference (zero) point for ruler depth measurements to ensure consistency (Goodison et al. 1981). Sampling may be difficult in very deep snow or where compacted layers and ice are encountered.

The quality of snow depth measurements depends largely on the judgement of the observer. The location of the individual sample points will influence how well the samples represent the actual snow depth. During the accumulation period, snow may build up around the ruler, resulting in overestimates of depth. Alternatively, it may be blown away, resulting in an underestimate (Goodison et al. 1981). During the melt period, depressions (wells) develop around the ruler, which may also result in the underestimation of snow depth. The most serious problems associated with manual measurements, other than observer error, involve sampling frequency and difficulty in accessing remote sites in the winter.

Obtaining continuous measurements of snow depth at remote sites requires instruments that can withstand environmental extremes with infrequent maintenance. Continuous automated snow depth measurements are usually obtained with an acoustic sensor. The distance between the sensor and snowpack is calculated by measuring the time required for the acoustic pulse to reach the snow surface and return to the sensor, multiplied by the speed of sound (Chow 1992). A correction for air temperature must be applied in the calculation of distance (Goodison et al. 1988). The reliability, accuracy, and relative low cost of this instrument make it an attractive tool. Various authors report that these instruments underestimate snow depth as a result of signal attenuation during moderate to heavy or drifting snowfall, depending on the frequency of sound used in the instrument (Goodison et al. 1984; Tanner and Gaza 1990). Newer instruments have an accuracy of ±1 cm or 0.4% of the distance to the snow surface, whichever is greater (Campbell Scientific [Canada] Corp. 2007).

Snow Water Equivalent

The water content of the snowpack is termed snow water equivalent (SWE). The SWE is "the weight of snow expressed as the depth of liquid water over a unit of area" (millimetres) (Brooks et al. 1991). It is the amount of water that would be obtained by melting a unit area of snow. In the open, SWE varies with the weather, location, and site. Under forest cover, SWE is influenced by canopy structure and distribution as well as by snowfall amount and pattern or frequency. In the south-central interior of British Columbia, within-stand variability in SWE has been shown to decrease with increasing snow accumulation (Winkler and Moore 2006).

The SWE can be measured gravimetrically by manually extracting at least two samples of snow collected from each layer of the snowpack as identified on the wall of a snow pit, and weighing or melting the samples to determine the volumetric water content (Pomeroy and Goodison 1997). Snow pit measurements most accurately estimate SWE and are often used to evaluate the results obtained using other techniques. This sampling method enables surveyors to identify ice layers, calculate densities for each layer, and make additional observations, such as temperature, within the snowpack (Woo 1997). The snow pit method is very time consuming and disturbs the snowpack over a relatively large area.

Most commonly, SWE is measured using a snow tube (B.C. Ministry of Environment 1981). Hollow snow tubes are made of steel, aluminium, or fibreglass, and have a sharp cutting edge at one end. As the snow tube is driven down through the snowpack to the ground, it cuts and collects a core of snow. The entire depth of snow must be sampled, including ice layers at the ground surface. This is done by pushing the tube into the ground to collect a small plug of soil or organic material. Snow depth is measured by reading the graduations on the tube. The snow tube is then lifted from the snowpack thereby extracting a core of snow. The soil plug is removed and the snow depth measurement is corrected by subtracting the depth of the plug. The tube and snow core are weighed. The combined weight, less the weight of the empty tube, gives the SWE (centimetres) of the core since the scale values account for the cross-section of the tube. The SWE equals the volume of water in the snow core (cubic centimetres) divided by the cross-sectional area of the tube (square centimetres). The volume of water (cubic centimetres) equals the weight of the snow (grams) divided by the density of water (assumed to be 1000 kg/m^3, or 1 g/cm^3). The snow tube most commonly used in British Columbia is the Standard Federal sampler, which has an inside orifice diameter of 3.77 cm (Coulson [editor] 1991) and an ice cutter at the leading edge.

The Standard Federal sampler is best suited to deeper snow and works well in snowpacks with compact or ice layers. It is not accurate at snow depths less than 0.25 m (Goodison et al. 1981; Woo 1997). Work et al. (1965) reported that the Standard Federal snow tube overestimates SWE by 7% in shallow, low-density snow and by 10–12% in deep, higher-density snow when compared with gravimetric samples. They did not observe any significant error associated with the weighing scales. Peterson and Brown (1975) reported that the standard snow tube overestimates SWE at densities greater than 25%. The overestimates increase with increasing density to a maximum of 12% at snow densities greater than 50%. In shallow snow (< 0.25 m), larger-diameter samplers provide more accurate measurements (Goodison et al. 1981). Additional problems may be encountered during snowmelt when liquid water in the snow sample drains through the slots in the Standard Federal snow tube, resulting in an underestimate of SWE.

The SWE can also be determined by removing and weighing all snow from a known area and dividing this weight by the volume (area sampled times the average snow depth) (Woo 1997).

Continuous SWE data can be obtained using a snow pillow, which consists of a rubber pillow filled with an antifreeze solution and placed on a levelled ground surface. As snow accumulates on the pillow, pressure resulting from the weight of the snow pushes antifreeze from the pillow up a standpipe, where a pressure transducer records the level of the solution. These pressure measurements are then converted to SWE based on relationships developed between the snow pillow readings and manual SWE measurements at the site.

Data from early snow pillows indicated that the smaller the pillow, the greater the overestimation of SWE in comparison with gravimetric measurements. This overestimate increases with increasing snow depth (Martinelli 1966). In British Columbia, the Ministry of Environment uses 3 m diameter pillows at automated snow stations in the provincial network (www.env.gov.bc.ca/rfc/about/snow-pillow.htm). Smaller snow pillows may underestimate accumulation rates during snowfall and may show increases in snowpack for several hours after the end of snowfall (Martinelli 1966). The major advantage of the snow pillow over a precipitation gauge is that it is not as strongly influenced by wind and is therefore more likely to approximate ground snow cover. Nevertheless, snow pillows are subject to unexplained diurnal variations, "bridging" by ice and snow over the pillow, instability of the pressure transducer, and damage to the pillow by animals and vandalism (Linsley et al. 1975; Storr and Golding 1976; McGurk 1986).

Palmer (1986) found that different relationships between snow pillow data and manual SWE measurements are required for the accumulation period and the melt period. Using manual measurements as the standard, an average absolute error of 5.6% was found during the accumulation period and an average error of 11.8% during the melt period. Based on these results, Palmer recommended that, when smaller errors are required, manual measurements should be made throughout the melt period.

Snow Density

Snow density is defined as the weight of snow per unit volume (Brooks et al. 1991). It is calculated by dividing the SWE by the depth of the snowpack. Density can also be measured for individual layers of snow within the pack by weighing a small sample of snow from each layer identified in a snow pit (Pomeroy and Goodison 1997). Fresh snow is commonly assumed to have a density of 100 kg/m^3 (10%), in which case fresh snow 1 m deep would yield 0.1 m, or 100 mm, of water. The actual density of newly fallen snow varies from storm to storm, during a storm, and with location, but is generally 50–120 kg/m^3 (5–12%) through the range of cold, dry to warm, and wet conditions (Goodison et al. 1981; Pomeroy et al. 1998). By the time snowmelt begins, the density of the snowpack will generally have increased to 300 up to 500 kg/m^3 (30–50%), with maximum density occurring while meltwater is flowing through the pack (Goodison et al. 1981; Pomeroy et al. 1998; Winkler 2001; Anderton et al. 2004). Pure ice has a density of 920 kg/m^3 (92%) (Brooks et al. 1991). Of the commonly measured snow parameters, density shows the least areal variability (Goodison et al. 1981), particularly during the continuous melt period (Anderton et al. 2004).

Snowmelt and Ablation

Snowmelt is the volume of liquid water in, and flowing out of, a unit area of the snowpack per unit time (millimetres per day). Meltwater outflow from the snowpack is generally measured only for research purposes. The rate of snowpack depletion or ablation is measured as the difference in SWE between melt season sampling dates divided by the number of days between surveys (millimetres per day). The ablation rate includes losses through sublimation, evaporation, and meltwater outflow, along with gains through precipitation. In cases when the snowpack disappears between sampling dates, the disappearance date can be estimated using ablation rates calculated for the preceding period. A continuous record of snow ablation can be obtained from snow pillow data, whereas the date on which snow has disappeared from a specific point can be obtained from snow depth sensor data.

Snow ablation can also be calculated from meteorological data using either a degree-day or an energy balance approach. Temperature-index models provide a simple method of estimating snowmelt from a single variable, air temperature; all other factors driving melt are parameterized in a single melt rate factor. Air temperature data are widely available, easy to measure, and provide a good indication of the energy available to melt snow. Temperature-index models for predicting snowmelt generally follow the form:

$$M = M_f (T_a - T_b) \quad (1)$$

where: M = snowmelt (millimetres over a selected time interval, often daily); M_f = melt-rate factor (millimetres per °C per day); T_a = index air temperature (°C; usually average or maximum daily); and T_b = base temperature at which no snowmelt is observed (°C, generally 0°C) (Gray and Prowse 1993).

The melt-rate factor and constant are derived by regressing observed daily melt against air temperature. These values are a function of atmospheric conditions, location, vegetation cover, and snowpack properties. Melt-rate factors reported for open areas range from 3.5 to 6 mm/°C per day), and for forested areas from 0.9 to 1.8 mm/°C per day). The temperature-index model can also be modified to include the depth of water added through rain (Gray and Prowse 1993).

The temperature-index method has been used to predict snowmelt at both a point and for entire basins with varying success. This method was reliable for predicting snowmelt over periods of a week to the entire season when applied in the same area for which it was calibrated (McGurk 1985; Gray and Prowse 1993; Rango and Martinec 1995); however, the accuracy of these models decreases over shorter time periods (Hock 2003). For example, daily melt estimates based on this method may be inaccurate early in the season, since nighttime refreezing of meltwater in the pack is not considered. Though simple, this method is not readily transferable because the constants are based on a specific set of spatial and temporal conditions. Temperature-index models are not generally useful for predicting spatial variability in snowmelt, as they do not account for the effects of shading, slope, and aspect. Models that incorporate solar radiation improve melt prediction both spatially and over time steps of a day or less (Hock 2003).

The energy balance, which represents the physical processes controlling melt, can also be used to estimate snow ablation:

$$Q_M = Q_R + Q_E + Q_H + Q_G + Q_P - Q_S \quad (2)$$

where: Q_M is the energy available to melt the snow (MJ/m^2 per day). The other subscripts indicate the source of energy used for snowmelt: energy from net radiation (*R*), latent heat (*E*), sensible heat (*H*), soil heat (*G*), and rain (*P*), and change in heat storage in the pack (*S*). The term Q_G is small (Adams et al. 1998), Q_S is negligible because the snowpack is close to 0° C during melt (Male and Gray 1981), and Q_P depends on the temperature difference between the rain and the snow. The daily energy in Q_R, Q_H, Q_E, and Q_P are converted to millimetres of water by multiplying by ($1000/[\rho_w \lambda_f B]$), where ρ_w is the density of water (1000 kg/m^3), λ_f is the latent heat of fusion (0.334 MJ/kg), and B is the thermal quality of the snow (assumed as 0.96) (Male and Gray 1981).

Although energy balance models of snowmelt are essential for comparing diurnal processes under varying environmental and forest cover conditions, direct measurement of the contribution of each individual variable is complicated and requires specialized equipment. Variables in the energy budget are often approximated using meteorological data such as air temperature, snow surface temperature, solar radiation, wind speed, and relative humidity (Walter et al. 2005). Energy balance calculations of ablation become even more complex under forest cover where the relationships between meteorological variables, forest cover, and snowmelt must be correctly represented. For example, in the estimation of Q_R from measurements of total irradiance, the amount of shortwave radiation reflected by a surface throughout the melt season must be known. The reflectance, or albedo, of fresh snow on the ground is high, in the range of 0.8–0.9 (Pomeroy et al. 1998; Spittlehouse and Winkler 2004). As the snow surface darkens from litter plus dust accumulation on the snow surface and changes in snowpack structure or the presence of water, the albedo may drop to 0.3–0.5 (Pomeroy and Goodison 1997; Pomeroy et al. 1998). Understanding this site-specific albedo decay is important to correctly estimate melt using the energy balance approach, and to model snowmelt. Consequently, the use of energy balance calculations of snow ablation is limited mainly to research studies.

Meltwater outflow from a snowpack can be measured directly using lysimeters. These devices capture meltwater as it drains out of the snowpack and measure either its weight or volume. The meltwater measured in a lysimeter is considered to be that which is available to run off or infiltrate into the soil. Lysimeters are classified as either enclosed or unenclosed. The collector in an enclosed lysimeter is surrounded by a barrier that completely isolates a column of snow. The collector in an unenclosed lysimeter is surrounded only by a raised rim (Kattelmann 1984). The lysimeter represents a discontinuity in the snowpack, resulting in a pressure gradient and a 2–3 cm saturated layer above the collector. Since the water pressure is greater in this saturated zone than beyond the perimeter of the discontinuity, water can flow laterally out of the collection zone, resulting in an underestimate of melt using unenclosed lysimeters. A low rim, 12–15 cm in height, is thought to contain the entire pressure gradient zone under most conditions (Kattelmann 1984). Before water can flow out of a lysimeter, storage in the capillary zone above the collector/snow interface and within the lysimeter itself must be filled (Kattelmann 1984). In areas with shallow snowpacks of less than 1 m deep, and in areas where snow in spring melts on tree canopies, drips to the ground, and freezes overnight, snow in a lysimeter box may become ice and block the lysimeter drain (Winkler et al. 2005).

Snow Distribution

For some applications, such as water supply modelling and flood forecasting, the areal distribution of snow cover over a watershed is of interest. Areal estimates of snow cover can be obtained through remote sensing or ground surveys. Methods for mapping snow distribution through remote sensing are described later in this chapter (see the "Hydrological Applications of Remote Sensing Data" subsection of the "Spatial Measures" section). Maps of snow cover distribution based on ground surveys are generally developed using data from surveys along transects covering the area of interest. The number and location of transects and sampling sites required increases with increasing variability in terrain, vegetation, and snow cover (Woo 1997). The area of interest should be stratified into zones of similar terrain, aspect, and vegetation. Within each zone, transect locations can be planned from maps or low-level aerial photographs without snow cover. However, these locations should be verified in winter to ensure that all snow conditions are represented and that the sampling design is feasible. Survey transects should be replicated within each zone.

Snow is measured at regular intervals along each transect. Since snow density is less spatially variable than snow depth, fewer snow density measurements are necessary along each transect than snow depth measurements. Woo (1997) suggested that for a 100-m transect in the Arctic, 20–40 depth measurements should be made and at least 1–2 density measurements should be taken. Woo further recommends that sample points are spaced 2–5 m apart in gullies and as far as 10–20 m apart on long uniform slopes. Pomeroy and Goodison (1997) suggested that in hilly terrain in the boreal forest, snow courses should be 120–270 m in length and sampled every 30 m. In open areas, however, snow course lengths could be longer and density measured every 100–500 m with five intervening snow depth measurements.

The number of sampling sites will vary with transect length and snowpack variability. If information regarding the variability in snow depth and density is available for similar environments and forest cover types, this information should be used to calculate the number of samples required to achieve a specified accuracy (Spittlehouse and Winkler 1996; Pomeroy and Goodison 1997). The average SWE for each transect can then be calculated from either the series of point SWE measurements, or by determining the relationship between snow depth and density, estimating density for points with only depth measurements based on this relationship, and calculating SWE (Steppuhn 2000). A reduction in the time spent on the less spatially variable snow density measurements allows for more time to be spent on additional snow depth samples to better capture the large variability in depth.

The average SWE for a watershed can be roughly estimated as the sum of the areally weighted snow survey results for each zone identified in the watershed. Snow disappearance can be approximated by depleting the snow measured in each zone late in the season using energy balance computations of snowmelt (Woo 1997) or using remote sensing techniques (see last section in this chapter). The spatial distribution of SWE is more accurately described through a combination of statistical techniques, distributed snowmelt modelling, and well-designed snow surveys, particularly in mountainous terrain (Anderton et al. 2004). In southeastern British Columbia, Jost et al. (2007) found that the spatial variability in SWE at Cotton Creek was best represented through a nested sampling design that accounted for variables controlling snow accumulation at both the small and large scales, including elevation, forest cover, and aspect. These authors also found that the relative influence of the variables changed from year to year and consequently recommended using an approach that combines field measurements and spatially distributed models to determine the variability in SWE across a watershed.

Snow Survey Design

When designing a snow sampling program, both the objectives of the survey and the required accuracy of the results should be carefully considered before establishing survey sites in the field. When snow survey data are used as an index to spring runoff, the survey equipment, procedures, and snow course should remain consistent over time. If the exact SWE value is important, then the representativeness of the survey sites relative to the landscape under study must be carefully considered (Goodison et al. 1981).

For forest management applications, comparisons of snow accumulation and ablation between forest cover types, between various cutting patterns and clearcuts, or between stands affected by fire, insects, or disease and healthy forest are often subjects of interest. It is useful to begin a new snow survey or research project by conducting a pilot study. In a pilot study, sufficient samples should be collected over a season to learn more about the number of samples necessary to detect differences considered of hydrologic significance as well as the sampling frequency most suitable to describe the variables of interest. For example, at Upper Penticton Creek, researchers were interested in determining differences in snow accumulation and ablation between forest dominated by mature lodgepole pine, forest dominated by mature Engelmann spruce–subalpine fir, and a clearcut.

Snow surveys at 50 sampling points in each stand were completed every 2 weeks in an initial sampling year. These data showed that to detect a 6-cm difference in April 1 SWE between a lodgepole pine stand and a clearcut, a minimum of 10 samples is required 95% of the time. If differences of 2 cm are of interest, 50 samples are necessary. Sample sizes of 10 and 50 were adequate to detect differences of 7 and 3 cm, respectively, between an Engelmann spruce–subalpine fir stand and a clearcut (Winkler and Spittlehouse 1995; Spittlehouse and Winkler 1996). The data also showed that sampling once every 2 weeks was not sufficient to determine differences in snow disappearance date between stands, since the snowpack typically disappeared within 2 weeks throughout the entire area.

Based on the first year of data, sampling intensity and frequency can be modified so that data analysis methods most appropriate to the questions asked can be used. Surveys should continue for a number of years to include the range of weather patterns and snowfall conditions typical of the study area. Snow survey design, site selection, and snow course layout considerations are described in B.C. Ministry of Environment (1981), Goodison et al. (1981), and Woo (1997). Properly designed snow sampling programs are key to successfully describing forest cover effects on snow accumulation and melt.

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Weather – Throughfall and Interception of Rain and Snow

DARRYL CARLYLE-MOSES

THROUGHFALL AND INTERCEPTION OF RAIN AND SNOW

Interception and subsequent evaporation of incident precipitation represents an important and sometimes dominant component of growing season and annual forest water balances. Given the quantitative importance of canopy interception loss (I_c), the acquisition of accurate estimates of this water output by hydrologists and watershed managers is imperative when calculating the water balance of an area of interest. With the exception of certain snow methods (see below), I_c is not measured directly, but rather estimated as the difference between incident precipitation (P) above, and understorey precipitation (P_u) below, the canopy:

$$I_c = P - P_u \quad (3)$$

A review of the literature suggests that the approaches to obtain P and P_u estimates are varied and as such this section focusses on those methods most frequently used (Table 17.2). Rainfall I_c is discussed separately from that of snow and examples are drawn from studies conducted within British Columbia where possible.

Rainfall Interception Loss

Incident rainfall

Rainfall incident upon a canopy is estimated using gauges situated above the canopy of interest or in a forest clearing close to the study stand. Much of the error associated with the measurement of rain is caused by wind-induced turbulence around the gauge opening (Legates and DeLiberty 1993). Since gauges located above a forest canopy are subjected to greater wind speeds than those in nearby clearings (see Oke 1987), the former approach may systematically underestimate incident rainfall. The placement

TABLE 17.2 *References for throughfall/interception methods*

Measure	References for methods
Incident rainfall	Brakensiek et al. (editors) 1979
Throughfall	Kimmins 1973; Spittlehouse 1998
Stemflow	Hanchi and Rapp 1998; Spittlehouse 1998
Incident snowfall	Golding and Swanson 1986
Snow interception loss	Lundberg et al. 1998; Winkler et al. 2005; Magnusson 2006

of rain gauges in a forest clearing, however, assumes that the rainfall input to the forest canopy is the same as that reaching the clearing. Thus, the clearing should be as close as possible to the study stand, especially in areas where a large proportion of rainfall is derived from spatially limited convective storms. In addition, rain gauges within a clearing must be situated far enough from surrounding trees so that rainfall input to the gauge opening is not obstructed. Brakensiek et al. (editors, 1979) suggested that the horizontal distance between the rain gauge and surrounding obstructions, including trees, should be at least two times the height of the obstructions. See the preceding subsection on precipitation for further information regarding the measurement of incident rainfall.

Understorey precipitation, P_u

Understorey precipitation associated with rainfall consists of throughfall (TF) and stemflow (SF), with TF being much more quantitatively important than SF in forest environments (see Dunne and Leopold 1978). Because of the variable nature of the overstorey canopy, the spatial variability of throughfall is often large. Overcoming this large variability may be accomplished by using several cylindrical point gauges within the plot of interest (Figure 17.1); however, the resources available and not the degree of spatial variability exhibited often dictate the number of gauges used by investigators (Levett et al. 1985). As a consequence, Kimmins (1973) suggested that many throughfall studies are of little value since certain statistical objectives were not met. Puckett (1991), based on equations used by Kimmins (1973) and Kostelnik et al. (1989), used the following equation to determine the number of gauges required to estimate mean throughfall to within a certain percentage of the mean at a desired confidence level:

$$n' = \frac{t^2_{(\alpha, n'-1)} CV^2}{CI^2} \qquad (4)$$

where: n' is the simulated number of gauges required, t is the Student t-value for a level of α with n'–1 degrees of freedom, and CV and CI are the coefficient of variation (%) and the confidence interval expressed as a percentage of the mean TF, respectively.

Using Equation 4, Puckett (1991) found that the number of gauges required to estimate mean event throughfall under a mixed hardwood canopy in Virginia to within 10% and 5% at the 95% confidence level ranged from 8 to 14 and 24 to 50, respectively. Similar gauge requirements have been found in other deciduous stands (e.g., Kostelnik et al. 1989; Price and Carlyle-Moses 2003). In coniferous forests, throughfall often exhibits greater spatial variability than in deciduous stands (e.g., Price et al. 1997) and thus adequately sampling this input will typically require more point gauges than in deciduous environments (see Kimmins 1973).

Point throughfall gauges may be kept in either fixed locations (e.g., Carlyle-Moses and Price 1999) or moved after each rainfall or certain time period has passed (e.g., Gash and Morton 1978). Some investigators (e.g., Lloyd and Marques 1988) suggest that for a given number of gauges, roving gauges provide more accurate estimates of cumulative throughfall than the fixed-gauge method since the standard error of the estimate may be summed quadratically in the roving but not in the fixed-gauge method. However, Carlyle-Moses (2002) found that season-long throughfall within a pine (*Pinus pseudostrobus* Lindl.) – oak (*Quercus* spp.) stand in northeastern Mexico could be estimated adequately using only a few fixed gauges. Thus, the increased accuracy given by the roving gauge approach may be inconsequential if the required water balance is at the season-long or annual time scales. In addition, the roving gauge approach does not increase the accuracy of single throughfall event estimates or is not useful for studies concerned with assessing either the temporal or spatial variability of this input (Kimmins 1973; Loustau et al. 1992).

Long trough collectors (Figure 17.2) have also been recommended (e.g., Kostelnik et al. 1989) since these gauges are thought to integrate the uneven delivery of throughfall. Although Reynolds and Neal (1991) concluded that insufficient evidence existed to support the claim that long trough collectors are better suited for sampling than cylindrical gauges, subsequent studies (e.g., Spittlehouse 1998) do suggest that the statistical objectives of a study can be met using fewer trough than point gauges. If trough gauges are used, then these troughs should be sufficiently deep to minimize splash or should be designed to eliminate splashing (Keim et al. 2005).

Employing Equation 4 to determine the number of gauges required to properly sample throughfall assumes that this input is normally distributed. However, the spatial variability of throughfall has been shown as non-random in several stands with this input increasing (e.g., Beier et al. 1993), decreasing (e.g., Robson et al. 1994) with increasing distance from the tree bole, or spatially random, but tem-

FIGURE 17.1 *Random distribution of point throughfall gauges in a soft-fruit orchard, Kamloops, B.C. (Photo: D.E. Carlyle-Moses)*

porally persistent (Keim et al. 2005). If throughfall exhibits systematic spatial variability, then a random array of gauges, especially a fixed array, may produce erroneous estimates of this input, and a stratified sampling design should be used (see Beier 1998).

As a guide to which throughfall sampling strategy should be used, the literature suggests that this input is systematically related to stand characteristics such as distance from the tree bole and leaf area index (LAI) for small rain events in most forest communities. For larger precipitation events (typically >5 mm), the systematic delivery of throughfall is often found in tree plantations (e.g., Alva et al. 1999) and in coniferous environments with moderate to large LAI values (e.g., Beier et al. 1993). In deciduous communities and stands of conifers where the LAI is less than 4 m^2/m^2, the spatial delivery of throughfall is typically random, especially if the canopies of individual trees overlap (Carlyle-Moses et al. 2004; Keim et al. 2005). Although throughfall may be estimated to within a relatively high degree of accuracy using the aforementioned methods, the errors associated with rainfall, throughfall, and stemflow are accumulated in the interception loss estimate, resulting in much larger relative errors. The relative error associated with the interception loss estimate depends on rainfall depth; given the errors associated with rainfall, throughfall, and stemflow, error values of ±15% or more should be expected on the absolute value of interception loss (D. Spittlehouse, B.C. Ministry of Forests and Range, pers. comm., Sept. 2006).

Stemflow

Stemflow is typically measured by fixing halved-tubing (to form a collar) around the circumference of a tree bole at approximately breast height. The collar is sealed to the tree bole using caulk sealant and the captured stemflow is directed via an unhalved section of tubing to a closed reservoir for subsequent measurement (Figure 17.2). Assuming that water has a density of 1000 kg/m^3, stemflow collected from individual trees may be scaled to the plot scale using the following equation:

$$SF_{depth} = \frac{SF_{vol}\, n}{A} \tag{5}$$

where: SF_{depth} is stemflow depth (millimetres), SF_{vol} represents the average SF volume (litres) collected from the sampled trees, and n is the number of trees within the stand area A (square metres).

Stemflow volume may be collected from a few "representative" trees within the study plot and then scaled to the stand area using Equation 5 (e.g.,

FIGURE 17.2 *Long throughfall trough collector emptying into a tipping-bucket rain gauge, Upper Penticton Creek Watershed Experiment, near Penticton, B.C. (Photo: D.E. Carlyle-Moses)*

Johnson 1990). However, this approach has been criticized since it is not always clear what "representative" means. Other scaling approaches (e.g., Hanchi and Rapp 1997) have been developed, with many based on the relationship between stemflow produced for a given precipitation depth and the diameter at breast height (dbh) of the sampled trees. Stand-scale stemflow is then derived by considering the dbh distribution of the stand.

Many canopy interception loss studies in British Columbia have not measured stemflow because this input was assumed as quantitatively inconsequential or simply estimated from previous studies (e.g., Beaudry and Sagar 1995). Although some studies found that stemflow is volumetrically inconsequential within coniferous stands of British Columbia (e.g., Maloney et al. 2002), the results of others (e.g., Spittlehouse 1998) suggest that stemflow may be an important component of understorey precipitation in these environments. Thus, assuming that stemflow is negligible may result in sizable overestimates of the quantitative importance of canopy interception loss.

The throughfall and stemflow collection method affects the questions that can be answered by the data collected. Continuous recording instruments such as tipping-bucket rain gauges (either as point collectors or used with troughs) allow for differentiation of individual storm events and an examination of rainfall intensity and duration influences on throughfall and stemflow. Alternatively, simple storage gauges can be used; however, data resolution is lost and separating storm events is difficult. Although storage gauges are less prone to instrumental failure, they require a greater frequency of field visits to collect measurements.

Snow Interception Loss

Incident snowfall

Snow incident upon a canopy may be estimated in an open clearing close to the study stand using various snow depth and snow water equivalent (SWE) measurement techniques including snow pillows, snow stakes, lysimeters, and snow surveys (see previous subsection on snow accumulation and melt; Dingman 2002). As with incident rainfall, the snowfall input to the clearing is assumed to be that which falls on the canopy of interest. However, the upward-increasing wind velocity pattern found over forest canopies is disrupted by clearings, resulting in increased snow deposition in these openings—especially if the diameter of the clearing is less than or equal to 20 times the height of the surrounding trees (Dingman 2002). Some studies (e.g., Golding and Swanson 1986) suggest that in relatively large clearings, higher wind velocities may develop, resulting in snow redistribution from the clearing to the surrounding forest. See previous subsection for further information concerning the measurement of snow.

Sublimation estimation

The sublimation and evaporation of snow from forest canopies is often estimated by measuring season-long snow accumulation below the stand(s) of interest and in a clearing, with the difference being the season-long interception loss. Nevertheless, this method is subject to the different snow deposition errors discussed above and provides relatively poor temporal resolution. Snow storage capacity and snow canopy interception loss have been estimated by continuously measuring the weight of cut trees with increases and decreases in weight representing snow accumulation and snow interception loss from the canopy, respectively (e.g., Lundberg et al. 1998). Magnusson (2006), however, suggested that the tree-weighing approach has limited practical applications since it cannot be conducted in dense forest, as the branches of neighbouring trees interfere with the measurements, and that the scaling of single-tree results to the stand scale is subject to large uncertainties.

Gamma ray attenuation techniques that provide vertical snow profiles within the canopy have also been suggested (e.g., Lundberg et al. 1998), but it is unlikely that this method will become a standard field technique because of radiation safety and high maintenance concerns (Magnusson 2006). Magnusson (2006) suggested that snow storage capacities and snow canopy interception rates could be estimated within a high degree of accuracy using an electromagnetic impulse wave velocity and attenuation technique. The velocity and attenuation of the electromagnetic wave, which is sent from an impulse antenna to a receiving antenna, are affected by ice and water within the canopy air space (see Bouten et al. 1991). Though promising, this technology is in its infancy. At present, the preferred method of estimating snow canopy interception loss in British Columbia is by measuring SWE accumulation differences between forest floors and forest clearings (e.g., Winkler et al. 2005). Errors are likely to arise using this method, however, since the assumption that seasonal snow interception is the difference between open clearing SWE and forest SWE may not be valid due to snowpack melt before the main melt season (D. Spittlehouse, B.C. Ministry of Forests and Range, pers. comm., Sept. 2006).

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Weather – Evaporation and Transpiration

GEORG JOST AND MARKUS WEILER

EVAPORATION AND TRANSPIRATION

Evaporation is the process by which water (or any other liquid) becomes gaseous without being heated to the boiling point. It is an important part in the water cycle and a key process in hydrology and ecology. Three kinds of surfaces are important in the movement of water back to the atmosphere: (1) vegetation, (2) soil, and (3) open water (Penman 1948). Evaporation of water from vegetation through plant leaves is called transpiration. In forested landscapes, three predominant components of evaporation (E) can be distinguished:

$$E = E_t + E_s + E_i \tag{6}$$

where: E_t is transpiration, E_s is soil evaporation, and E_i is interception evaporation. Evaporation is also often referred to as evapotranspiration at a stand or watershed scale. Although evaporation from open water bodies is of minor importance in the water balance of most terrestrial systems (except for lakes and reservoirs), great attention is given to it because open water bodies provide a reproducible surface of known properties. The complex mechanisms of evaporation from vegetated surfaces or soils are often approached by relating the water losses from vegetation and soil to water losses of open water under the same meteorological conditions.

In a benchmark paper published in 1948, Penman combined the energy balance with the mass transfer (or aerodynamic) method and derived an equation to compute the evaporation from an open water surface using standard climatological records of sunshine, temperature, humidity, and wind speed. Penman (1948) called this direct evaporation from open water surfaces the "potential evaporation" (e.g., the amount of water that could be evaporated by the atmosphere if sufficient water was available). The original Penman equation was further extended to other vegetated surfaces (Penman already studied evaporation from bare soil and grass) by introducing resistance factors. The most common form is the physically based combined heat balance and aerodynamic equation of Penman and Monteith, which includes an aerodynamic resistance and a surface resistance. Both resistances are combinations of several single resistances. The surface resistance describes the resistances of vapour flow through stomata openings, total leaf area, and soil surface. The aerodynamic resistance describes the resistances from the vegetation upward and involves friction from air flowing over vegetative surfaces. For greater detail, see Brutsaert (2005).

Because aerodynamic and surface resistances depend on both the vegetation and the soil, the potential evaporation varies for each surface. To overcome the necessity to define unique evaporation parameters for each (vegetated) surface in the calculation of potential evaporation, the concept of a reference surface was introduced. Early attempts used open water as a reference surface; however, the large differences in aerodynamic, surface, and radiation characteristics to vegetated surfaces made it difficult to relate evaporation measurements of vegetated surfaces to free water evaporation. As a result, potential evaporation is usually related to a short, green grass surface with adequate water, which incorporates the biological and physical processes involved in evaporation. The Food and Agriculture Organization recommends the Penman-Monteith method to compute potential evaporation from a green grass reference surface since this method provides consistent potential evaporation values in all regions and climates (Allen et al. [editors] 1998).

Besides climatic controls, soil water availability and the structure of vegetation limit evaporation. Trees control water uptake by opening and closing stomata, and the stomata are in turn controlled by potassium availability. During drought or time with high evaporative demand, plants close stomata, which increases the surface resistance (by decreasing leaf conductance). As a result, actual evaporation—the quantity of water that is actually removed from a surface by evaporation—is lower than the potential evaporation. Koestner (2001) and Schume et al. (2004) showed that transpiration is more frequently limited by low surface conductance than by soil drought.

Evaporation is either measured directly through micro-meteorological methods or indirectly through the water balance. Several different methods to measure evaporation have been developed (Wilson et al. 2001). Table 17.3 provides an overview of common methods used to directly or indirectly estimate evaporation. Each method has its own representative spatial and temporal scale; applications outside this scale can be difficult. Methods to measure evaporation also differ in what is measured: some methods measure total evaporation whereas others measure only one or several components of evaporation, such as transpiration, interception evaporation, or soil evaporation.

Lysimeter

A lysimeter is a container that isolates a volume of soil (undisturbed or disturbed) hydrologically from its surrounding soil. The isolated soil volume is intended to be as representative as possible of the undisturbed surrounding soil and vegetation. Lysimeters are either weighing or non-weighing. Weighing lysimeters provide a direct measure of total evaporation and are also used to study chemical fluxes and water percolation into the groundwater. The advantage of using a weighing lysimeter is that the water vapour fluxes are obtained independently of the surface energy budget. Lysimeters are reliable for measuring evaporation to 0.02–0.005 mm of equivalent water depth (Parlange and Katul 1992; Yang et al. 2000). The measurement principle is based on the soil water balance equation:

$$\Delta S = P + Q - R - E \qquad (7)$$

The change in soil water (ΔS), measured by weighing, is a result of precipitation (P), percolation or groundwater flow (Q; can be negative), runoff (R), and evaporation (E). Interception is one component of evaporation. Lysimeters are usually constructed such that all runoff water percolates, thus evaporation is computed as:

TABLE 17.3 *Methods for direct or indirect measurement of evaporation or components of evaporation (E_t = transpiration, E_s = soil evaporation, E_i = interception) with approximate representative spatial scale and the highest meaningful resolution time scale for each method*

Method	Direct/indirect measurement	Component	Spatial scale (m²)	Time scale
Lysimeter	Direct	$E_t + E_s + E_i$	10^1	Hourly
Catchment water balance	Indirect	$E_t + E_s + E_i$	$> 10^6$	Annual
Throughfall [a]	Direct	E_i	10^2	Daily
Soil water balance (automatic sampling)	Indirect	$E_t + E_s$	10^0	Daily
Soil water balance (manual sampling	Indirect	$E_t + E_s$	10^3	Weekly
Evaporimeter (Class-A pan)	Direct	E_s (open water)	10^2	Daily
Sap flow	Direct	E_t	10^2	Hourly
Bowen Ratio/energy balance	Indirect	$E_t + E_s + E_i$	10^4	Hourly
Eddy covariance (above canopy)	Direct	$E_t + E_s + E_i$	10^4	Hourly

a For details, see subsection "Throughfall and Interception of Rain and Snow" (pg. 575).

$$E = P + Q - \Delta S \quad (8)$$

Although some lysimeters include trees as vegetation, the use of lysimeters in the study of evaporation from forests is limited by the small area that can be covered; as a result, only a small area can be represented. The building and maintenance costs of this method are high compared with the others.

Catchment Water Balance

An annual estimate for evaporation can be computed from the catchment water balance:

$$E = P + Q - R - \Delta S \quad (9)$$

which is the same as Equation 8 but includes runoff. The evaporation term is a residual in the balance equation and errors in other terms, such as assumptions about deep percolation (Q) or spatial representation of precipitation measurement. Annually, ΔS is assumed to be zero and Q is often assumed to be zero so that the total annual evaporation becomes the residual between annual precipitation and total annual runoff:

$$E = P - R \quad (10)$$

Although information about between-year processes cannot be obtained from annual evaporation estimates (and detection of annual trends that cannot be backed up with process information are questionable), the catchment water balance is a useful method for comparison of different watersheds and for confirmation of other methods (Wilson et al. 2001). Despite all the disadvantages, the catchment water balance is the method with the highest spatial aggregation.

Soil Water Balance

The soil water balance method computes transpiration and soil evaporation from changes in soil water storage using estimates or assumptions of drainage and interception:

$$E_{t,s} = P + Q - E_i - R - \Delta S \quad (11)$$

At the stand scale, it is usually assumed that inflow equals outflow so that R can be omitted. Canopy interception or interception evaporation can be estimated from throughfall (and if applicable from stemflow) measurements. In most studies (because of a lack of knowledge), it is assumed that no drainage occurs below the depth of the deepest measurement; groundwater flow (Q) is also assumed to be zero. The soil evaporation and transpiration component of the total evaporation is then the residual between precipitation minus throughfall minus change in soil water storage (ΔS). The advantages of this method are its simplicity and the possibility to relate the contributions of transpiration and soil evaporation to different soil layers. Spatial and temporal scales depend on the technology used to measure the soil water storage. Automatic soil moisture probes (e.g., automatic time domain reflectometry probes; see subsection later in this chapter on "Soil Moisture Measurement Methods") give high temporal resolution data (minutes); however, the number of probes and thus the spatial extent and the representative scale are limited by equipment costs. With more probes, and thus a greater spatial extent of sampling with less expensive manual techniques, temporal resolution suffers (Schume et al. 2004; Jost et al. 2005). A combination of a few automated soil moisture measurements (at high temporal resolution) with many manual measurements (at high spatial resolution) makes it possible to assess evaporation over larger areas in daily or subdaily time steps.

Evaporimeter (Class-A Pan)

Evaporimeters (e.g., the World Meteorological Organization recommended Class-A pan) have been used since the 18th century to estimate potential evaporation. Class-A pans are still used in Canada and worldwide because of their simplicity, low cost, and ease of application (Stanhill 2002). In most situations, pan evaporation is higher than evaporation from vegetated surfaces (Chiew and McMahon 1992). It is adjusted by multiplying by a pan coefficient that varies with the vegetation surface and the state of vegetation development (Allen et al. [editors] 1998),

$$E = k_p \times E_{PAN} \quad (12)$$

where: E is total evaporation, k_p is the pan coefficient, and E_{PAN} is the pan evaporation. Problems are associated with the pan coefficient because it is influenced by numerous factors and integrates many variables (i.e., pan, pan surroundings, site conditions, fetch, relative humidity, radiation, and wind speed), which all contribute to uncertainties. The main problem in using pan evaporation data is that specific pan coefficient values must be found for each application, although some representative values from other studies and corrections to actual evaporation exist (Allen et al. [editors] 1998).

Sap Flow

Sap flow techniques measure the water passing through the conductive xylem of a tree stem based on thermodynamics (some methods use other principles). Heat pulse velocity (Swanson and Whitfield 1981; Green et al. 2003), trunk segment heat balance (Cermak et al. 1973), thermal dissipation (Giles et al. 1985; Tatarinov et al. 2005), and heat field deformation (Cermak et al. 2004) are the most common methods and are all based on a similar principle—that is, the relationship between heat dissipation, assessed from temperature differences at a heated and outside a heated part of the stem, and sap flow. Heat pulse velocity measures the linear velocity of sap flow by applying a heat pulse. The main advantage of this method is that it requires no reference temperature, so that the influence of the surrounding temperature gradients is minimized. The main limiting factor of this method is that it is not a true real-time measurement, since it requires a steady state after applying a heat pulse to take a reading, which takes time. Constant heating approaches, such as trunk segment heat balance and thermal dissipation (most commonly used in North America; e.g., www.dynamax.com/), represent a truly continuous measurement, but these methods require a reference temperature, which can be a source of errors, and require more power for operation. Sap flow can be measured at high temporal resolution and, in conjunction with climate and soil moisture data, provides insights on environmental controls of the transpiration or soil evaporation process. Heat losses or gains that cannot be attributed to stemflow, installation problems (probes need to be vertical), and sap flow variability along the radius (different results depending on location along the stem) are potential sources of error with stemflow methods. Knowledge of the anatomy of the sample trees is a prerequisite for proper installation of sensors. Extrapolation of transpiration to the stand scale is not straightforward. It requires a selection of representative trees for a given stand and an appropriate scaling technique (for more details, see Cermak et al. 1995, 2004; Tatarinov et al. 2005). The approximate number of sample trees is at least 10 for homogeneous stands and more for older heterogeneous stands (Koestner 2001).

Bowen Ratio / Energy Balance

The modified Bowen-ratio / energy balance method can be used to estimate air–surface exchange rates of water vapour and other gases (e.g., CO_2) by measuring differences in concentrations between two heights (Black and McNaughton 1971; Blad and Rosenberg 1974; Spittlehouse and Black 1979; Meyers et al. 1996). The Bowen ratio (β) is the ratio between sensible (H) and latent (λE) heat flux,

$$\beta = \frac{H}{\lambda E} \qquad (13)$$

In conjunction with the energy balance, the Bowen ratio is used to partition the available (incoming) energy into sensible and latent heat. With the latent heat of vaporization of water, the total evaporation rate can be computed from the latent heat flux. The Bowen ratio β can be measured by,

$$\beta = \gamma \frac{\Delta T}{\Delta e} \qquad (14)$$

where: ΔT and Δe are the temperature and vapour pressure difference between the two measurement levels (i.e., 3 m), and γ is the psychrometric constant. The accuracy of the evaporation estimate is directly related to the accuracy of the temperature and vapour pressure measurements. In situations with large gradients, the accuracy of the evaporation estimate is less than ±15%; small gradients decrease the accuracy to values between ±10% and ±60% (Spittlehouse and Black 1979; Perez et al. 1999). For consistent data the nighttime period and periods during and after precipitation must often be rejected (Perez et al. 1999). From the time and the spatial scale, the Bowen-ratio/energy balance method is comparable to the eddy covariance method. Since the costs are substantially less than the costs for eddy correlation and the sensor system required for eddy correlation is less robust, the Bowen-ratio/energy balance method is still widely used.

Eddy Covariance

Eddy covariance has been used for approximately 40 years to study CO_2, H_2O, and CH_4 fluxes over various surfaces in homogeneous and complex terrain (e.g., Schume et al. 2005). Eddy covariance, when applied to evaporation, analyzes the vertical mass flux density of water vapour statistically as the covariance between vertical wind speed (e.g., the vertical vector of wind "eddies" [*w*]), and water vapour density (ρ_v) (Falge et al. 2001a, 2001b),

$$E = \rho_a \overline{(w' \times \rho'_v)} \qquad (15)$$

where: ρ_a is the density of the air, primes are the fluctuations around the mean, and the overbar indicates time averages (15–30 mins). A measurement frequency of 10 Hz (10 measurements per second) is usually required to capture the high-frequency contributions to the flux (eddies). For low-frequency contributions, advective fluxes for example, atmospheric fluxes are averaged over 30–60 minutes.

Eddy covariance is most accurate on homogeneous vegetation with flat terrain and steady atmospheric conditions (Baldocchi 2003). Diversion of any of these conditions from ideal introduces inaccuracies that can be partially fixed with approved methods such as source area analysis, corrections for advective fluxes, and correction for density fluxes (Leuning and Moncrieff 1990; Paw U et al. 2000). Falge et al. (2001a) analyzed 28 eddy sites and found an average data coverage of 65%. This does not mean that eddy systems are unreliable but certainly points out that running eddy covariance measurements requires continuous attendance. Eight eddy covariance systems are running within the Fluxnet Canada network, and six of these are in forested landscapes (www.fluxnet-canada.ca/).

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Water Quantity – Streamflow

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STREAMFLOW

Streamflow integrates all the hydrologic processes and storages upstream of a particular point in time and space and is one of the most widely measured quantities of the hydrological cycle. The characteristics of streamflow response of a forested watershed are important for understanding channel stability, sediment transport, and ecological function, as well as a wide variety of other management concerns.

Documenting the variability of streamflow response at a given gauge location involves: (1) collecting discrete measurements of water level (stage) and streamflow (discharge); (2) referencing a continuous record of water levels relative to a known or assumed datum; and (3) establishing an empirical relationship between stage and discharge, commonly known as a rating curve. The level of monitoring effort and quality of gauging site directly affects the quality of the resulting hydrometric data record. Poor site selection or infrequent gauge visits may lead to a hydrometric record that does not meet the required monitoring objective. Although some adverse conditions for measurement of open channel flow are unavoidable, it is best to avoid or mitigate errors that may affect the quality of the resulting hydrometric record.

This subsection is concerned with reviewing common standards and practices for the measurement and monitoring of streamflow for small- to medium-sized watersheds (flow generally less than 50 m^3/s). Monitoring streamflow in larger basins requires a substantial investment in occupational safety training and equipment typically feasible only for large hydrometric monitoring agencies. Church and Kellerhals (1970), Terzi (1981, 1983), Rantz (1982), and the Resources Information Standards Committee (1998, 2009) serve as valuable references for more information on streamflow gauging and standards of practice.

Gauging Site Selection

Gauging site selection can be one of the most important tasks in the collection of a hydrometric record. A good gauging site will maximize the data quality and minimize the work required to generate the resulting hydrometric record.

Of primary importance in gauging site selection are the sensitivity and stability of the control. Most natural channels have a number of different downstream features that influence the stage measured at a given location at different flows. Collectively, these features are referred to as the "control" (Rantz 1982). The stability of the control can be affected by shifts in the channel configuration, debris entrapment, or vegetal growth on the bed and (or) banks. Ideal gauging locations are upstream of channel constrictions, bedrock sills, or significant breaks in channel slope where the flow remains entirely within the channel banks over the range of possible flows and unaffected by backwater from tributary confluences, lakes, or tides. The site should have no complicating sources of local stage variability caused by shifting bed, vegetal or ice growth, debris entrapment, or turbulence. The stability of the control directly affects the stability of the rating curve relationship and subsequent monitoring effort required to ensure that the rating curve is valid within the desired level of precision.

The sensitivity of the control plays an important role in translating changes in measured stage into fluctuations in estimated discharge. Insensitive control(s) not only diminish the measurement of flow variability, but can also directly affect the quality of the derived rating curve. In many small forest streams, an artificial control such as a V-notch weir may need to be constructed to make the measured stage sensitive to small changes in the observed discharge. The environmental impacts, sediment entrapment, and hydraulics must be carefully considered before construction.

It is not necessary for the streamflow measurement (the "measurement section") to be co-located with the gauge; however, the reach must not gain or lose flow between the two locations. The measurement section should be situated within a reach where the characteristics of flow are best suited to the measurement method. In many cases, shifting the measurement location or method (depending on stage) will be required. It is important to overlap measurements at different locations and (or) methods to ensure that no bias is introduced into the stage-discharge rating.

Measuring Streamflow

Several methods are available to obtain discrete measurements of streamflow at a given point within a watershed. The methods fall into four basic categories: (1) velocity-area, (2) dilution, (3) volumetric, and (4) hydraulic (Table 17.4). The velocity-area methods are, by far, the most common methods of streamflow measurement. Dilution methods are generally appropriate for steep, turbulent channels. Volumetric methods are best suited to gauging small discharges. Hydraulic methods are based on simplified equations of open channel flow and precise geometry of the control.

Measurements of streamflow using the velocity-area method require a series of point velocity and flow depth measurements to capture the lateral and vertical distribution of stream velocities at a cross-section. More than 20–25 verticals (or "panels") may be required to effectively sample the horizontal distribution. The method assumes that the vertical velocity distribution follows a parabolic or logarithmic profile with the mean velocity of the water column approximated by point measurements at 0.6d, where "d" is the depth of the stream (or 0.2d and 0.8d for depths greater than 0.75 m) (Terzi 1981); however, the assumption of a smooth parabolic or logarithmic velocity profile in streams of most interest to forest hydrologists is likely false. Most studies that formed standards of practice in velocity-area methods were conducted at the beginning of the 20th century and sampled large rivers or flumes (see Pelletier 1988). The horizontal, vertical, and temporal velocity distributions of mountain streams have not been systematically examined to verify the assumptions implicit in the general method. This makes the choice of measurement method and site selection of paramount importance when deriving a high-quality gauging record.

Several different methods can be used to integrate unit discharge over the entire cross-sectional flow area, the most common being the mid-section method. No more than 5% of the total measured flow should be contained within any one panel (Terzi 1981; Rantz 1982).

Several technologies can be employed to measure velocity-area, including the traditional current meters (e.g., Pygmy or Price meter) as well as acoustic technologies (e.g., FlowTracker™). In general, the time required to adequately sample both channel

TABLE 17.4 *Summary of methods for streamflow measurement*

Method	Technique	Technology	Ideal stream conditions	Reference
Velocity-area	Wading	Mechanical, acoustic	Steady uniform flow, shallow, medium velocity, smooth bed	Terzi 1981
Velocity-area	Bridge	Mechanical, acoustic	Steady uniform flow, medium velocity, smooth bed	Terzi 1981
Velocity-area	Ice	Mechanical	Competent uniform ice cover, no slush ice, steady uniform flow, medium velocity, smooth bed	Terzi 1981
Dilution	Constant rate	Ionic compounds, fluorometric dyes	Steady turbulent flow	Moore 2004b
Dilution	Slug	Ionic compounds, fluorometric dyes	Steady turbulent flow, limited channel storage and hyporheic exchange	Moore 2005
Volumetric		Bucket/stopwatch	Small streams, freefall at gauging location	Resources Information Standards Committee 1998
Hydraulic		Weir	Steady uniform flow	Church and Kellerhals 1970; Resources Information Standards Committee 1998

area and velocity distribution makes the technique difficult to apply in rapidly varying flow conditions. The velocity-area technique is generally unsuitable for high-energy streams for four main reasons (Kilpatrick and Cobb 1985; Pelletier 1988):

1. Bed roughness elements may be large in relation to channel flow, making it difficult to measure cross-sectional area of flow and velocity accurately.
2. Most technologies available for velocity measurement by the velocity-area technique perform poorly at stream velocities outside the range of meter calibration or at shallow depths (or at boundaries) (Pelletier 1988).
3. The technique requires the introduction of a meter into a high-velocity flow, which may result in over-sounding caused by frictional drag on the meter assembly and expose the field technician to undue occupational hazards.
4. Under conditions of rapidly varying flow, the time to measure velocity-area may be excessive.

Streams with these characteristics may be better measured using dilution methods.

The Acoustic Doppler Current Profiler (ADCP) has been adapted to fluvial environments over the past decade and provides a more complete sample of the velocity-area distribution of flow in a much shorter period of time compared with traditional velocity-area methods. Acoustic meters are incapable of sampling the entire water column. All acoustic meters require a blanking distance for the transducers and electronics to recover from the high-energy transmit pulse. Although the blanking distance is relatively small, it can become significant in proportion to total cross-sectional area in wide, shallow streams. Acoustic meters are not designed for measuring high velocities, moving bed, or highly turbulent stream reaches. Therefore, it may be several years before ADCP technology is adapted for use in high-energy mountain streams.

Dilution methods have an advantage over traditional velocity-area techniques for measuring steep turbulent flows, typical of mountain environments. Although dilution methods have been used for several decades, the use of these methods as an operational technique is limited to a few national hydrometric agencies (e.g., Switzerland, New Zealand) and research applications.

The general procedure for dilution gauging is to introduce a known concentration of tracer solution (or mass) to the streamflow either at a constant rate or as a slug. The dilution effect is then measured at a downstream location of complete mixing. Although several tracers can be used (e.g., ionic compounds such as NaCl and KBr, and fluorometric dyes, such as Rhodamine WT and Uranine), all have common properties in that these substances are:

- conservative,
- found at low concentrations in the ambient stream water,
- nontoxic for the concentrations and exposure times typically associated with discharge measurements,
- highly water soluble, and
- detectable at very low concentrations.

Sodium chloride (NaCl) is often used as a tracer because it is cheap, readily available, and measured using conductivity meters. Flows of up to 15 m^3/s can be reliably measured using salt in solution (Moore 2004a) and higher when the salt is added to the flow in dry form (Hudson and Fraser 2005). A practical upper limit for salt dilution is constrained by the mass of salt that can be reasonably handled. Dilution methods using fluorometric dyes are recommended for gauging higher flows because of the lower detection limit of monitoring devices and limited presence of fluorescence in natural stream waters. These characteristics allow for lower injection masses relative to the salt technique for a comparable flow. Fluorometric dyes vary in light sensitivity, toxicity, and the ability to be absorbed or detected.[1] Users should refer to the specific properties of individual fluorescent tracers before applying at a gauging location.

Dilution techniques work on the assumption that:

- the streamflow is unchanging during the trial;
- the tracer is completely mixed with streamflow at the point of measurement;
- a measurable difference is evident between tracer wave and background concentration; and
- no loss of tracer occurs between injection and measurement sections.

In general, a minimum mixing length of 25 channel widths is required to ensure complete mixing

1 Weiler, M., H. McGuff, and J. Trubilowicz. 2005. Evaluation of the effectiveness of tracer methods for discharge estimation. Univ. British Columbia, Vancouver, B.C. Unpubl. manuscr.

of tracer with the natural stream waters (Day 1977). In turbulent channels, the mixing length may be reduced to less than 10 channel widths (Hudson and Fraser 2005). Conducting trials at various flow conditions will help determine the minimum mixing length required to ensure complete mixing. If the dilution method is conducted using the slug technique, it is best to situate the injection and measurement sections to minimize the effects of in-channel storage (e.g., pools). These channel elements will attenuate the tracer wave through the reach and lengthen the measurement duration required to effectively sample the entire tracer wave. However, the dilution method may be inappropriate in reaches containing large storage elements under conditions of rapidly varying flow.

Volumetric methods determine discharge based on the time taken to fill a container of known volume. The technique is most practical for gauging small flows (< 5–10 L/s). To conduct discharge measurements, the best locations are those in which the water surface freefall allows the placement of a container that will capture the flow. It may be possible to divert flow to a length of plastic pipe or flume that will create a hydraulic head difference sufficient to place a container beneath the exiting flow (Resources Information Standards Committee 1998). The container should be of large enough volume to minimize filling-time errors. Multiple sampling is encouraged to minimize the effect of flow pulsations that can establish longitudinally within the culvert.

Hydraulic methods of discharge measurement require the establishment of a control structure at which the flow over the crest is critical. Flow is estimated (Church and Kellerhals 1970) from standard weir and flume equations. The environmental effects, sediment entrapment, and hydraulics must be carefully considered before weirs or flumes are constructed. In general, however, it is best to rate the control structure by direct measurement using any of the suitable methods in Table 17.4. Deviations of measured flow from standard equations can be caused by debris or algal growth at the control or the presence of an approach velocity. Flow and water level should be measured before and after any maintenance of the control structure.

Measuring Water Surface Elevation

The stage of a river is the height of the water surface above an established datum. The record of stage is used with the stage–discharge relationship to produce estimates of discharge in the absence of direct measurements of discharge. The accuracy of discharge estimates relies on the accuracy of stage measurements as well as the validity of the stage–discharge relationship. The following discussion examines in more detail the controls on the accuracy of this relationship.

To obtain accurate and reliable stage data, the station gauge and benchmarks must refer to a known or arbitrary datum plane (Terzi 1984). To avoid the possibility of negative gauge heights, it is necessary to select a datum that is sufficiently below the elevation of zero flow. The gauge should be referenced by at least two and preferably three stable benchmarks associated with the gauging station but independent of each other and independent of the gauging structure (Terzi 1984). The datum of the stream gauge should be checked against benchmarks at least two to three times per year to ensure the stability of the vertical control. More frequent surveys should be conducted following any sign of channel instability, flooding, ice jams, vandalism, or any event that may have disturbed the gauge reference. Surveys should reference the same water column as the recording device (e.g., staff gauge, transducer). In turbulent streams, river stage may fluctuate up to several decimetres. A portable stilling device installed temporarily in the flow can dampen turbulence and allow reference of the water level to the gauge datum.

Staff gauges are the most common devices for manually measuring stage in rivers (Resources Information Standards Committee 1998). Staff gauges are typically graduated in 0.005-m increments with achievable precision of ±0.001 m; however, flow turbulence, clarity of water and gauge plate, and pressure waves on the leading edge of the staff gauge can considerably reduce measurement accuracy. Crest stage gauges are simple, reliable devices for measuring the peak river level at manual gauges. These gauges serve as a back up to recording gauges in case of failure (Terzi 1983).

Several technologies, such as pressure transducers and float recorders, exist for measuring stage continuously. Generally, continuous monitoring devices should have the ability to measure stage within ±0.003 m (Rantz 1982). These devices require some form of stilling of stream turbulence to record a clean trace of water level for hydrologic purposes (i.e., discharge estimation). Stilling of the water surface elevation can be done physically using a stilling well or digitally by time-averaging of successive sensor readings. Digital averaging of sensor readings is increasingly used to achieve a realistic hydrological signal; however, this may mask important hydraulically generated stage events related to ice formation (Hamilton 2004).

Establishing a Stage–Discharge Relationship

It is possible to develop a time series of discharge estimates from a continuous record of stage data by deriving a stage–discharge rating curve. The use of this relationship is based on the premise that the free surface of the monitored stream channel is sensitive to variations in discharge and that this surface varies only in response to changes in the volume of water conveyed by the channel. Ideally, a stream reach suitable for using this relationship is one with a stable control feature; a steady, uniform flow; and no complicating sources of local stage variability (e.g., tributary flow, irregular cross-section, turbulence, weeds, bed movement, debris entrapment, ice). In reality, it is almost impossible to continuously satisfy all of these requirements. The following discussion encourages practitioners to avoid these problems where possible or to employ mitigation measures when problem avoidance is impossible. A more general treatment of rating curves is found in the *Manual of Standard Operating Procedures for Hydrometric Surveys in British Columbia* (Resources Information Standards Committee 1998) and the *Manual of British Columbia Hydrometric Standards* (Resources Information Standards Committee 2009).

Curves were traditionally prepared by hand drawing a smooth curve through a scatter plot of stage and discharge measurements and extracting a look-up table of values from this curve. Most practitioners now prefer to use numerical methods to fit the stage–discharge equation (Equation 16) to the data:

$$Q = B\,(H - H_o)^{\alpha} \tag{16}$$

where: Q represents discharge; B *is* a calibrated coefficient; H represents stage; H_0 is zero flow; and α is a calibrated exponent.

Mosley and McKerchar (1993) reported that values of α are typically near 1.67 for rectangular, 2.17 for parabolic, and 2.67 for triangular channels. The term H_0 can be estimated by channel surveys to determine an elevation of zero flow, although it is more commonly determined through calibration.

The fitting of a rating curve requires several assumptions regarding site and flow characteristics. These assumptions are often difficult to justify at the scale of streams of interest to forest hydrologists. Furthermore, assumptions are required on the uncertainty inherent in the stage and discharge measurements. Petersen-Overleir (2004) challenged the regression techniques commonly used for parameter estimation, which do not account for the heteroscedasticity typically associated with sets of discharge measurements. Ultimately, the same data can be used to produce multiple interpretations of a rating curve (Jonsson et al. 2002). This problem of multiple, equally likely, solutions is often referred to as "equifinality."

Hand-drawn curves allow subjective weighting of the curve through a scatter when the distribution of measurement uncertainty is variable, which is why agencies such as the U.S. Geological Survey and the Water Survey of Canada favour this technique. Simplistic approaches such as trend-fitting data in a spreadsheet assume that all data points have equal weight in determining curve parameters, an assumption that is almost never true. More sophisticated curve-fitting techniques are available that account for heteroscedasticity in the data (e.g., Peterson-Overleir 2004), but forest hydrologists rarely have the data density needed for robust resolution of the curve using sophisticated statistical techniques. The dominant factors controlling the validity of a rating curve are the quality and density of field measurements. No known method of fitting a curve to data can compensate for inadequate fieldwork.

A typical flow frequency distribution results in reduced opportunity to obtain measurements at the extremes. The quality of measurements near the extremes of stage can be compromised by less than ideal survey conditions. These measurements have the greatest leverage on the shape of the rating curve because of the low density of measurements near the ends of the curve. For this reason, a curve should not be extrapolated to above double the discharge of the highest measurement or below half the discharge of the lowest measurement. As easy as it is to extend a curve in a spreadsheet and as difficult as it is to schedule a field program to be on site at or near the extreme events, this rule of thumb should only be ignored with extreme caution.

Equation 16 can be too simplistic for many natural channels since it defines the rating relationship to a unique control feature of fixed geometry. Many natural channels are influenced by multiple control features that become dominant at different river stages. This problem is typically dealt with by partitioning the curve into multiple segments

(Peterson-Overleir and Reitan 2005), with each segment representing a unique relationship. Although a change in control may be evident at low or high stages, sufficient measurements may not be available to support the definition of a new curve segment. Over-segmenting the curve may produce unanticipated results when extrapolating beyond the domain of observed data. Curve segmentation should be supported by physical evidence (e.g., channel surveys) and a sufficient density of measurements above and below the hinge point to fully resolve the shape of both segments.

The control feature may become submerged at high stage or overbank flow may occur at flood stage. Stage and discharge measurements are needed over the full range of stage to accurately define the mathematical model that is best suited to fit the stage–discharge relationship and to ensure that no bias exists in fitting of model parameters. Extrapolating above or below the range of available measurements is almost always necessary but doing so requires confidence that a good fit has been obtained and that the fit is valid for the full extent of extrapolation. Clarke (1999) and Yu (2000) discussed how the uncertainties in defining the stage–discharge relationship are manifest in systematic uncertainties in calculated flow statistics. Evaluation of the uncertainty in the relationship requires an examination of several systematic sources of measurement and model error.

Diagnostics and commonly used treatments for stage–discharge-related uncertainty are provided in Table 17.5. Residual plots that show relative error plotted against some relevant variable are an extremely important diagnostic tool. In these examples, relative error is shown on the ordinate axis plotted against time (t), stage (H), Julian date, or discharge (Q). In addition to the residual plots, a stage–discharge curve is used as a diagnostic for the biased calibration example. A water-level hydrograph and precipitation hyetograph (P) are also useful in diagnosing for episodic effects. Nevertheless, examination to detect systematic errors in measurement accuracy will be based on scrutiny of the original field notes, which requires non-graphical analysis.

Few, if any, locations in British Columbia have a stage–discharge relationship that is valid year-round without frequent surveys and maintenance. For example, ice conditions eliminate the potential for using a stage–discharge relationship for 6 months or more per year at some locations.

When data providers are queried on discharge data accuracy, they frequently cite the technological literature provided with the instruments (e.g., water level accurate at 0.01% of full scale). However, the actual operating conditions experienced in the field may be quite different from the laboratory conditions under which the calibration was developed. The performance of the instrument is just one link in a long chain that influences accuracy and reliability of the discharge record. Currently, no practical method is readily available to explicitly quantify the uncertainty in discharge data derived using a stage–discharge relationship. The uncertainty will depend on the answers to the following questions.

1. Are the assumptions implicit in the measurement method (see discussion above on “Gauging Site Selection”) valid in the actual field conditions experienced?
2. Is the assumption of a stable gauge datum valid? (See discussion above on “Measuring Water Surface Elevation.”)
3. Is the calibration of the water-level sensor routinely checked for stability and validity over the full range of stage and during all conditions in which it is deployed?
4. Is the stilling mechanism (mechanical or digital) appropriate for the ambient conditions and are data available at a sufficient resolution to fully resolve the response characteristics of the stream?
5. Are sufficient stage and discharge measurements available over the full range of stage to distinguish between the need for a simple curve versus a compound (segmented) curve? Do field surveys of the channel support the chosen level of stage–discharge curve complexity?
6. Are sufficient stage and discharge measurements available over the full range of stage to average random measurement errors, allowing for unbiased parameter estimation?
7. Are the assumptions of steady, uniform flow valid continuously over time and at all stages?
8. Does stage vary in response to any other variable other than discharge (e.g., ice, weeds, debris)?
9. Are the control features stable over time?
10. Are the control features sufficiently sensitive to changes in discharge at the precision at which stage observations are made?

It takes a great deal of training and experience to make the decisions needed to use a stage–discharge relationship effectively, especially in high-energy

TABLE 17.5 *Diagnostics and commonly used treatments for stage–discharge-related uncertainty*

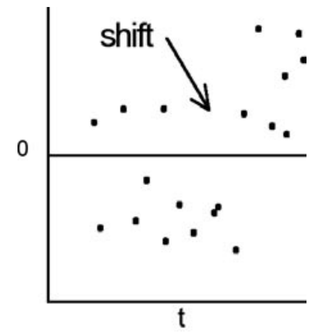
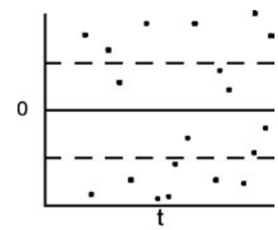
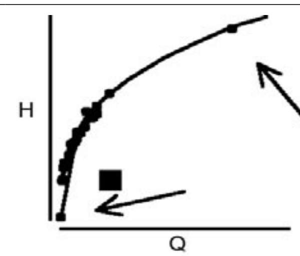
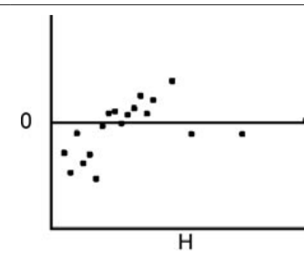
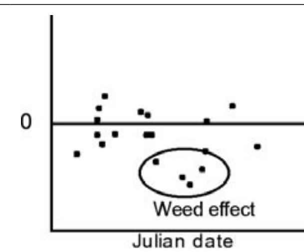
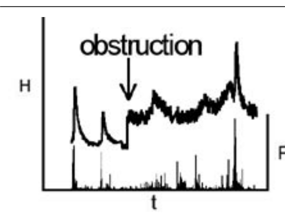
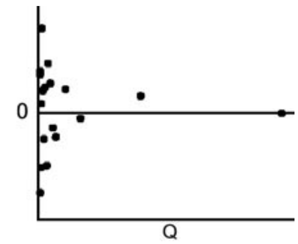
Uncertainty	Diagnostic	Treatment(s)	Example
Unstable control	Time-series plot of discharge residuals display a trend or pattern	Apply time-based shift corrections Update curve to after-shift condition Build (rebuild) control Move station	
Unsteady flow/ non-uniform flow	Discharge residuals have greater random error than would be expected based on measurement accuracy	Apply stage-based shift corrections Move station	
Biased calibration	High-leverage measurements	Obtain measurements over a wider range of stage	
Model too simplistic	Discharge residuals plotted against stage display a trend or pattern	Recalibrate curve; if residuals are still non-random, increase the segmentation of the curve, ensuring that each segment is well supported by a sufficient number of measurements	
Seasonal effects (e.g., weed growth, ice effect)	Discharge residuals plotted against Julian date display a trend or pattern	More frequent measurements during affected periods Censor backwater-affected estimates Develop backwater relationships	
Episodic effects (e.g., debris entrapment, beaver dams)	Rapid change in stage without hydrologic explanation (e.g., independent observations of precipitation)	Censor suspect data Move station Shift corrections to estimate affected data	

TABLE 17.5 *Continued*

Uncertainty	Diagnostic	Treatment(s)	Example
Low flow imprecision	Plot of relative residuals against discharge shows high scatter at low flow	Improve accuracy and precision of low-flow stage and discharge measurements Build a control structure that is more sensitive to low flows	
Measurement bias	Detailed scrutiny of measurement field notes to ensure that field conditions experienced do not violate measurement assumptions	Censor invalid measurements	

mountain streams. The effective use of the stage–discharge relation for computing discharge requires the correct choice of:

- gauging site,
- suitable measurement methods for local conditions,
- suitable sensing/data-logging technology for local conditions, and
- timing and frequency of visits for calibration/validation of the relation and for site maintenance.

Poor choices in any of the above will result in substandard data. A stage–discharge relationship can provide reliable, continuous discharge estimates as long as all of the underlying assumptions are valid. Good data will be supported by documentation demonstrating that the threats to data quality, as discussed in this subsection, have been successfully avoided or mitigated. Data lacking this documentation should be used only with extreme caution.

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Soils – Soil Moisture

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SOIL MOISTURE

The unsaturated zone in the soil or bedrock links atmospheric processes and vegetation with groundwater and streamflow. Soil moisture, or soil water content, of the unsaturated zone is temporally dynamic, and spatially variable and hence highly influential on other processes. Soil moisture regulates infiltration, percolation, evaporation, and transpiration; acts as a temporary storage of precipitation for generating streamflow; and directly influences the thermal regime of the soil, soil respiration (CO_2 efflux), and vegetation dynamics (e.g., forest growth and species composition). Understanding and measuring the soil water content in watersheds are therefore of great interest to forest hydrologists. Yet even with this importance, soil moisture measurements are neither performed regularly in operational settings nor in many experimental forested watersheds. The temporal and spatial knowledge of soil moisture, however, is a very important variable that helps to calibrate and validate hydrological models and is necessary to understand many hydrological processes in forested watersheds.

Soil Moisture Measurement Methods

Soil water content is described in two ways: (1) on a mass basis (gravimetric water content), or (2) on a volume basis (volumetric water content). Given the water content, the degree of saturation can be calculated as the ratio between volumetric water content and porosity. The water content can be determined in the laboratory or using field methods (Table 17.6).

In the laboratory, a field-extracted intact core of known volume is weighed, dried at 105° C for 24 hours for mineral soils and 70° C for 48 hours for organic soils, and then weighed again. The difference is used to compute the volumetric water content. In the field, water content is commonly measured by time-domain reflectometers (TDR) or frequency-domain reflectometers (FDR), which have recently replaced neutron probes as the primary method of instrument-based soil moisture measurements. The TDRs operate by measuring the propagation velocity in the soil of an electric pulse that is related to the dielectric permittivity (ability of material to transmit an electric field) or dielectric constant, which varies with water content (Hook and Livingston 1996; Spittlehouse 2000). The FDRs determine the resonant frequency with the greatest amplitude, which also varies with water content. The volumetric water content is determined for both methods through calibration with the dielectric permittivity. For a more detailed overview of the TDR and FDR techniques, refer to Topp and Ferré (2006).

Water content is also determined indirectly by measuring the soil water potential, or more specifically, the soil matric potential (also referred to as matric suction, capillary potential, soil water tension, or soil water suction). Matric potential is negative and becomes increasingly negative as the soil dries. The matric potential is related to the soil moisture by the soil moisture characteristic curve (also soil moisture release curve or water retention curve) and is an important property of the soil. This relationship strongly depends on the soil texture but also on other soil properties such as soil structure, organic matter, and bulk density. If this relationship is known, soil matric potential can be measured and then the soil water content calculated. Measuring the soil matric potential at multiple locations allows the determination of the direction of water movement in the soil. This is possible because water moves from an area of higher to lower potential. The concepts of field capacity and permanent wilting point are used to evaluate the current state of the soil with regard to water available for plants (Weiler and McDonnell 2004). Matric potential is commonly measured using tensiometers for potentials in the range of saturation to about 0.01 MPa (0–1 bar). Drier conditions require soil hygrometers, soil moisture blocks, or heat dissipation sensors (see details in Durner and Or 2005). Similar to tensiometers, these instruments depend on equilibration of a reference porous medium with the surrounding soil and most require individual calibration to infer soil water potential.

TABLE 17.6 *Volumetric water content measurement methods*

Instrument	Time step	Accuracy[a] (% WC)	Comments	References
Soil sample	Single, destructive	0.2% (approx.)	A "wet" weight of the soil sample is measured and then the sample is oven-dried and a dry weight measured. The volume of the sample is taken by measurement (core) or by a water displacement method.	Topp and Ferré 2002
Tensiometer	Continuous with pressure transducer	3–5%	Tensiometers measure matric potential, and if water retention characteristic of soil is known, water content can be calculated. For wet and moist soil.	Durner and Or 2005
Moisture blocks	Continuous	10%	Moisture block measures soil matric potential. Works in wet and dry soils. Not accurate.	Freeland 1989
Time-domain reflectometer	Continuous, intrusive	2–3%	Instrument measures the dielectric permittivity of soil by measuring the time it takes for an electromagnetic wave to propagate through the soil. The volumetric water content is determined through calibration with the dielectric permittivity.	Topp and Ferré 2006; Spittlehouse 2000
Capacitance probe (or frequency-domain reflectometers)	Continuous, intrusive	3–5%	Measures the capacitance of the soil surrounding the probe, which depends on the water content. Frequency range between 100 to 150 MHz minimizes salt and conductivity factors.	Topp 2003
Neutron probes	Single and logged	<3%	A decaying source emits fast neutrons into the soil. The neutrons are backscattered and slowed by the presence of water. A detector measures the amount of slowed neutrons and, via calibration, the soil water content.	Hignett and Evett 2002

a With calibration.

Limitations, Applications, and Interpretations

The most common source of error for all soil moisture or soil matric measurement techniques is a poor contact of the sensor with the surrounding soil material. This can result in an error of 5–10% water content. To ensure good contact, the sensor should either be placed into a predrilled access hole with a diameter at the position of the sensor slightly smaller than the diameter of the sensor. When measuring matric potential, the sensor can also be placed in a larger predrilled hole (particularly necessary in stony soils or soils with a high root content). There, a slurry of non-swelling fine material or sieved local soil is filled in, which is used to provide hydraulic contact between the sensor's surface and the soil. Ensuring good contact is particularly difficult in stony soils.

The different measurement techniques also have different results when used in frozen soils. The TDR and capacitance methods do not detect ice, so these instruments only provide measurements of liquid water content in frozen soils. The neutron probe measures the total water content of a frozen soil, as does the gravimetric method. Tensiometers do not work well in frozen soil as the internal liquid is prone to freezing. The measurement volume of the different methods is highly variable as well, with the neutron probe providing the largest soil volume over which measurements are integrated.

As listed in Table 17.6, the different measurement techniques have different accuracies depending on the measurement principle. These accuracies can be achieved only if the sensor is calibrated to the particular soil, because all continuous measurements do not directly measure water content but use another property to infer soil water content. Without site-specific calibration, accuracy can be easily two to three times lower. Recently, Czarnomski et al. (2005) compared the accuracy and precision of commonly used "low-cost" soil moisture sensors in natural forest soils in the Pacific Northwest and the influence of temperature and site-specific calibrations. They concluded that without site-specific calibrations, the mean difference in water content for most probes is around 5–10% and that temperature also influences sensor precision.

As with many other point measurements in hydrology, the interpolation of soil moisture measurements to the watershed scale is difficult. Several processes influence the spatial and temporal patterns of soil moisture in a watershed and, hence, the measurement locations influence the calculated mean water content or its assumed distribution (e.g., Western et al. 2004). At one location, the soil moisture varies with depth and the variations are usually largest within the root zone. The mean soil moisture of one location can only be determined accurately when using vertically inserted probes or a profile of horizontally inserted probes that are integrated over the depth. The mean soil moisture content of a watershed or larger area can either be determined with many sensors (e.g., Spittlehouse 2000) or by using geostatistical approaches to determine the spatial correlation length and the number of required sensors to measure the mean soil moisture (Schume et al. 2003). Nevertheless, the temporal dynamics of only one or a small number of sites within a watershed reveals considerable information that can be used to better understand hydrological processes and soil–vegetation interactions in a watershed.

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Soils – Soil Thermal Regime

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SOIL THERMAL REGIME

The soil thermal regime is important in terms of water movement, soil and road stability, and plant growth. Frozen soils restrict infiltration of melted snow and rain, and result in the development of ice lenses and frost heaving; cold soils can influence plant survival and growth (Male and Gray 1981; Spittlehouse and Stathers 1990; Stathers and Spittlehouse 1990). The thermal regime is quantified by soil temperature (°C) and soil heat flux (W/m^2, MJ/m^2 per day). The heat content of a unit volume of soil depends on soil bulk density, specific heat, and temperature. Site location, atmospheric weather conditions, ground cover, and the physical properties of the soil profile (water content, texture, coarse fraction, organic matter) affect soil temperature (Devine and Harrington 2007). The location of the site (latitude, elevation, slope position and gradient, and aspect) influences the receipt of solar energy. Atmospheric weather conditions determine the supply of radiation, heat, and water to the ground surface. Vegetation and snow cover modify the effects of atmospheric weather by shading and insulating the soil surface. The thermal and hydraulic properties of the soil profile, in turn, govern its response to the changing supply of heat and water (Stathers and Spittlehouse 1990).

Distinct diurnal and annual soil temperature cycles are a response to changes in the energy balance at the soil surface. Soil temperature changes with depth as heat is redistributed within the profile. Heat is conducted down gradients of temperature (i.e., from warmer to cooler regions). Consequently, as the surface absorbs solar radiation and warms during the daytime, heat is slowly conducted into the cooler underlying soil. At night, the ground surface cools by emitting longwave radiation to the atmosphere and vegetation cover; most of the heat that was stored in the profile during the day is conducted back toward the cooler surface and lost to the atmosphere. The diurnal variation in soil temperature is greatest at the soil surface and decreases rapidly with increasing depth. The slow rate of heat transfer through the profile also causes temperatures at depth to lag increasingly behind changes in surface temperature. The diurnal cycle results in changes in soil temperature down to the 0.3–0.5 m depth. The annual solar cycle produces annual variations in soil temperature down to 5 m. During the spring and early summer when the soil near the surface is warming, deeper soil is still cooling as the winter portion of the cooling wave penetrates into the profile. The soil temperature at the 1–2 m depth typically lags behind near-surface temperatures by about 3 months (Stathers and Spittlehouse 1990).

The limited data available suggest that forest soils in the central and southern interior of British Columbia usually do not freeze to great depths during the winter. Some initial freezing may occur in the top 0.3 m of the profile if the snowpack is late in developing or is lost during winter; however, the snowpack insulates the soil from cold winter air temperatures and reduces the rate of heat loss from the profile. The soil may freeze down to about the 0.5–1.0 m depth at sites with very little snow cover and continuously cold winter weather. The diurnal temperature variation in the soil profile is also negligible during the winter even though atmospheric temperatures are variable (Stathers and Spittlehouse 1990).

Measuring Soil Temperature and Heat Flux

Soil temperature is measured with electrical, mechanical, or chemical sensors. One-point temperature measurements for soil survey can be determined with adequate accuracy using metal-sheathed, mercury-in-glass, bimetallic strip, resistor, or thermocouple thermometers. These instruments are relatively inexpensive and durable. Thermistor, platinum resistor, or thermocouple thermometers are used with data loggers to record temperatures continuously. Sensors should have a low heat capacity and high thermal conductivity.

Temperatures should be measured at specified depths and times so that comparisons between sites are possible. Standard depths are 0.01, 0.05, 0.1, 0.2, 0.5, 1, 1.5, and 3 m, although in most cases it is not necessary to measure the temperature at all of these depths. Substantial spatial variation in the top 0.2 m of the soil is caused by the variation in surface cover and shading of the surface. In this case, it is necessary to replicate measurements, which can be done by using more sensors or by connecting a number of sensors together in series or parallel. A sensor is installed by digging a hole and inserting it into the undisturbed soil at the required depth. At least 0.1 m of cable should be buried at the same depth of the sensor to minimize heat transfer down the wires for other depths.

Soil heat flux is measured with thermopile-based sensors. Heat flux sensors must have good contact with the soil and are usually placed about 0.05 cm below the surface. The temperature change with time and knowledge of the thermal properties of the upper 0.05 cm are used to adjust the heat flux to that at the soil surface. Soil heat flux can also be calculated from the temperature gradient and knowledge of the soil thermal properties (Stathers and Spittlehouse 1990).

Soil Temperature and Heat Flux Data Availability

Soil temperature data are not readily available. Some historical data exist but few of these sites continue to measure soil temperature and they are not located in forests. Few research sites in British Columbia measure soil temperature and even fewer measure soil heat flux.

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Physical Water Quality – Suspended Sediment

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SUSPENDED SEDIMENT

Fluvial sediment—particulate matter moved by water—is commonly divided into two groups: (1) bed load (which is also referred to as benthic sediment), and (2) suspended sediment.

Bed load primarily consists of coarse sand and gravel-sized particles and is quantified in units of mass (i.e., kilograms). This material is moved downstream by rolling or sliding along the bottom. It can also be transported by saltation, in which particles skip or bounce by momentarily being pushed into the lower portion of the water column and then fall out again within a few seconds. Transport of coarse sand and gravel requires higher stream energies and, as such, is usually associated with peak flow events or high-gradient streams. For more information on bed load sampling, see Resources Information Standards Committee (2002).

As its name implies, suspended sediment is material that is held in suspension in a water column for a variable period of time and is measured as a ratio of these two components (e.g., milligrams per litre). Particles greater than 62 µm (i.e., sand) will fall out of the water column in seconds once the water is calmed. Silt-sized particles (2–62 µm) can remain in suspension for minutes in still water, while clay-sized particles (< 2 µm) can remain in suspension indefinitely. In most natural drainage systems, however, primary particles tend to flocculate to form larger clumps of sediment.

Suspended sediment is derived from the erosion of surficial materials and streambanks and the re-suspension of channel bed deposits. The quantity and type (e.g., particle size, composition) of suspended sediment in natural runoff varies with the kinetic energy of the moving water and the type of surficial material within the drainage. For a given stream, suspended sediment typically increases with increasing discharge. Furthermore, watersheds that contain a large amount of silt- and clay-sized particles tend to produce more suspended sediment than basins in which the parent material is dominated by a coarser substrate (i.e., with a limited supply of fine material). As such, high suspended sediment loadings are usually associated with peak flow events in watercourses that pass through easily eroded soils. In British Columbia, large low-gradient rivers tend to have high suspended sediment yields (Church et al. 1989).

High suspended sediment concentrations can occur as the result of natural erosion processes. In some cases, however, poor land use practices can increase suspended sediment concentrations above naturally occurring levels. Road construction near water bodies, combined with the removal of surface vegetation, greatly increases the potential for erosion and transport of sediment to a stream channel. Furthermore, road surfaces, ditches, and associated clearing widths tend to enhance surface runoff, which will increase the movement of fine material into natural drainage networks.[2]

Natural and anthropogenic changes on unstable terrain can also result in elevated suspended sediment concentrations. Slope failures resulting in landslides or debris flow in gullies can move large quantities of material into stream channels (Hogan 1986). Although the suspended sediment portion of this material may pass through the watercourse fairly rapidly, changes to the stream channel from deposition of bed load material can exacerbate bank erosion and thereby elevate suspended sediment concentration over the long term (Hartman et al. 1996).

Suspended sediment can also reduce the effectiveness of chemical disinfection treatments, such as chlorination, and physical treatments, such as ultraviolet irradiation. High suspended sediment concentrations are also associated with conditions that are harmful to fish. For example, particles in the water may irritate fish gills. In response to these stimuli, fish gills produce a mucus-like substance that

2 Pierre Beaudry and Associates Ltd. 2004. Water quality monitoring and SCQI surveys in FMA 9900037 for Canfor Grand Prairie: 2004 field season. Prince George, B.C.

reduces the capacity of the membrane to exchange gases, which causes stress in the fish. Fine sediment can also be of concern when it covers or fills spawning gravels or rearing habitat containing fish food such as benthic invertebrates. See Caux et al. (1997) for more information on water quality standards in British Columbia.

Collection of Suspended Sediment Data

Quantifying suspended sediment involves both field collection and laboratory procedures. Grab samples of suspended sediment can be collected either manually or with an automated system. A large sample (e.g., 1000 mL) tends to provide better data as it is more easily analyzed in the laboratory.

The frequency of sampling should reflect the purpose of the study, but suspended sediment tends to vary more widely during peak flow events than during low flow conditions (B.C. Ministry of Environment 1999). Suspended sediment concentrations tend to be higher as streamflow increases (as represented on the rising limb of a hydrograph) where the sediment is not as supply-limited as when streamflow is decreasing. Hudson (2001a) suggested that this might be caused by the impact of raindrops dislodging and then entraining exposed surficial material. A seasonal variation is also common as higher suspended sediment concentrations are usually found before the annual peak flow event (Beschta 1978). Both daily and seasonal hysteresis has been observed during snowmelt runoff in the province's Interior (Jordan 2006). Given this high degree of variability, it is important to increase the frequency of sampling during peak flow events.

To obtain samples during short-duration events, an automated sampler (e.g., ISCO 6712 or Sigma 900) should be controlled by an instrument capable of measuring stage height. If a turbidity probe is used to initiate the automated water sampler, then the triggering event should be a number of successive high readings as opposed to a single high value (e.g., four successive readings when the minimum turbidity value is > 30 nephelometric turbidity units [NTUs]). Regardless of the instrument used to initiate the automated sampler, the controller should be programmed to minimize the time interval between successive samples (e.g., 20 minutes). Failure to include a temporal restriction that spaces out samples over the event will result in the automated sampler filling up very quickly with samples that contain virtually the same suspended sediment concentration. The sampling frequency during peak flow events should reflect the size of the watercourse, with the sampling of a smaller stream occurring more frequently because of its flashiness. After a sample has been extracted from a watercourse, it should be stored in a cool, dark environment to minimize the effects of algae or other contaminants. For complete details on suspended sediment sampling protocols, see the Resource Information Standards Committee archive at: http://archive.ilmb.gov.bc.ca/risc/pubs/aquatic/index.htm.

If the study is trying to quantify suspended sediment from a specific source (e.g., a road crossing or gully), then two monitoring stations should be installed: one upstream of the sediment source and the other below it (Caux et al. 1997). This procedure allows the background suspended sediment concentration to be subtracted from the downstream measurements and thereby localizes the difference to a specific stream reach.

Turbidity as a Proxy for Suspended Sediment

Turbidity is a measure of the cloudiness of a liquid and is usually quantified in nephelometric turbidity units (NTUs). Organic matter (e.g., algae) or inorganic particles (e.g., silt) can cause turbidity. Generally, water colour is not a good indicator of turbidity, as dissolved compounds such as tannins can cause the water to appear dark without influencing its cloudiness. Turbidity is usually measured by passing a beam of light through a water sample and quantifying the scattering of the photons. Using these methods, turbidity can be measured very accurately in the laboratory (e.g., to within 0.1 NTU) or with less precision under field conditions. See Anderson (2005) for more information on the function and calibration of turbidity probes.

To obtain a more complete understanding of the sediment regime of natural watercourses, many researchers have worked towards establishing a relationship between suspended sediment and turbidity (e.g., Jordan 1996; Hudson 2001b). The relationship between these two variables is determined by measuring the turbidity of the grab samples at various suspended sediment concentrations and then applying this relationship to a data set of continuous turbidity measurements. Unique combinations of sediment composition result in different relationships between turbidity and suspended sediment concentrations; therefore, relationships must be established for each basin studied.

The proper deployment of turbidity sensors can be difficult. Each brand of turbidity sensor will have a different-sized viewing window (i.e., the area in front of the sensor that is scanned to obtain a measurement). This area must be kept clear of all obstructions (streambed, woody debris, etc.) otherwise a false reading will be recorded (D & A Instrument Company 1993). The sensor must also be located so that it is not affected by ambient light (i.e., solar radiation). In shallow streams, installing a turbidity probe in compliance with these two constraints can be challenging. In warmer bodies of water, the sensor on the turbidity probe can become fouled by algae or aquatic organisms if not serviced regularly. Some turbidity probes are equipped with wipers that are designed to reduce fouling, but these units require a more robust power source to supply this increased demand for energy.

Locating turbidity probes and pump sampler intakes in low-gradient streams with stable channels is relatively straightforward; however, in steep, high-energy streams, it can be very difficult (Figure 17.3). The probability of missing data or of damaging the installation during peak flow events can be very high. Turbidity probes that are installed in high-energy streams are also subject to erroneous readings when bubbles entrained in the water column are mistaken for suspended sediment. To reduce this effect, the probe should be installed where turbulent flow is minimized. Additionally, the probe must be placed on an angle so that bubbles do not congregate on the face of the sensor (McVan Instruments 2002). In high-energy streams, a program of manual sampling may be preferable to automated monitoring.

When recording the measurements taken by the turbidity probe, it is important to record the minimum reading taken during the logging interval, as this measurement usually provides the best correlation with suspended sediment concentration. For example, if the probe scans the water column every 30 seconds and the data logger has a recording interval of 6 minutes, then the smallest of the 12 readings should be logged.

Laboratory Analysis of Sediment Samples

The suspended sediment concentration of a water sample is usually determined by either evaporation or filtration. If the sample contains sediment that readily settles under the influence of gravity and has a low dissolved solid concentration, then the evaporation method of analysis can be used. This procedure involves siphoning off most of the supernatant water and then placing the residual sample into a drying oven in which the remaining water is evaporated. The mass of the sediment is then determined to the closest 0.1 mg using an analytical balance (American Society for Testing and Materials 2002).

For samples that contain less than 10 000 mg/L of sand and less than 200 mg/L of clay, filtration is the preferred method of analysis. Typically, a porcelain or glass crucible that has been fitted with a glass fibre filter is dried in a convection oven, allowed to cool in a desiccator, and weighed to obtain the tare mass. The sample is then poured through the crucible, which is attached to a vacuum system to accelerate the filtration process. Once the sample has been filtered, the crucible and filter are placed back into the drying oven at 105° C and the remaining moisture is evaporated. The crucible and filter are allowed to

FIGURE 17.3 *An example of a suspended sediment monitoring station (under low flow conditions). The probes are mounted on rebar, which is secured at the bottom by placing it into a section of open-bottomed copper pipe. The top of the rebar is bent to 90° and inserted into a hole in the 2 × 6″ board. This arrangement keeps the instruments secure during peak flow events, but also allows them to be easily removed for servicing. (Photo: P. Marquis)*

cool in the desiccator and then reweighed to determine the mass of the sediment (American Society for Testing and Materials 2002).

If organic matter makes up a large part of the sample (i.e., > 5% by dry weight) it can be removed by either chemical oxidation or combustion. Oxidation is the preferred method because it has less of an effect on the mineral component of the sample. This procedure involves skimming off any floating material and adding a solution of hydrogen peroxide to a concentrate of the original sample (Guy 1969). Organic material can be an important component of the sediment load of some streams. For some studies, it may be preferable to include it in the sample analysis, or to analyze duplicate samples separately for organic and inorganic components.

A particle size analysis can also be performed on suspended sediment samples. The traditional procedure involves wet sieving the sample with a 250-mesh (0.062 mm) sieve to separate the sand from the finer material. The sand fragment is then dried, re-sieved using appropriately sized screens, and weighed. The fine fragment is analyzed using the pipette method. This procedure uses Stokes' Law to predict settling times for different-sized particles. The fine fragment is treated with a dispersing agent and the slurry is placed into a settling cylinder. A pipette is then used to withdraw 25-mL samples at various depths after a predetermined interval. The samples are placed in an evaporation oven and weighed to determine the mass (Guy 1969). Most modern laboratories, however, use laser diffraction techniques to quantify fine sediment. See Cooper (1998) for details on the applicability and limitations of this procedure.

Summary

The selection of an appropriate monitoring site is the most important factor to consider when collecting suspended sediment data because turbulence and changing stream channel conditions can easily lead to erroneous readings. The collection of high-quality data relies on frequent maintenance visits to the monitoring sites and periodic recalibration of the instrumentation. Furthermore, the data must be closely scrutinized to detect and remove erroneous readings. If the resources are available, data quality can be greatly improved by installing duplicate monitoring sites, as this makes the identification of questionable values much easier (e.g., when woody debris becomes temporarily lodged against a sensor).

When collecting and analyzing suspended sediment data, there will be a large amount of temporal variability within a specific stream and spatial variability between different watercourses. Therefore, making inferences about the suspended sediment regime of a particular stream requires the collection of a number of years of data; however, these conclusions may not be valid when applied to a different watercourse.

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Physical Water Quality – Stream Temperature

ED QUILTY AND R.D. (DAN) MOORE

STREAM TEMPERATURE

Stream temperature controls many aspects of stream ecology. It influences rates of biological and chemical processes, limits dissolved oxygen concentrations, and affects the life history and behavioural ecology of aquatic organisms. Summer stream temperature typically increases following the removal of riparian forest canopy, as a result of forest harvesting, wildfire, and (or) other disturbances (Nitschke 2005; Moore et al. 2005a). Urban development, agricultural land use, water withdrawals (e.g., for irrigation), and impoundments can also influence stream temperature, primarily through changes to shading and streamflow (Klein 1979; Hockey et al. 1982; Quinn et al. 1997; Webb and Walling 1997). Because these changes can potentially harm aquatic ecosystems, particularly cold-water species such as salmonids (Beschta et al. 1987; Nelitz et al. 2007), substantial attention has focussed on the effects of land use on stream temperature.

This subsection introduces methods for stream temperature measurement and data processing. It begins with a discussion of the ranges of stream temperature variability typically found in British Columbia, then introduces the technologies available for measurement, data processing, and field installation of sensors.

Stream Temperature Variability

Stream temperature varies diurnally and seasonally in response to changes in the energy available for heating. The absolute rates and relative importance of various heat transfer mechanisms depend on a range of time-varying climatic factors, such as solar radiation, air temperature, humidity, and wind speed, as well as site characteristics, such as the amount of shading by riparian vegetation (Teti 2004) and rate of groundwater discharge (Brown 1969; Webb and Zhang 1997; Story et al. 2003; Moore et al. 2005b). The change in temperature associated with a given heat input depends on stream depth: shallower streams are more sensitive to heat inputs than deeper streams. Because stream depth is correlated with streamflow, variations in stream discharge play a secondary, though still important, role in controlling stream temperature variability (Webb et al. 2003; Moore et al. 2005b).

Most streams in British Columbia follow an annual stream temperature cycle, which varies somewhat depending on hydroclimatic regime (Figure 17.4). Streams draining low-elevation coastal catchments tend to remain above freezing through winter, except during occasional periods dominated by cold air masses. Interior streams, on the other hand, tend to stay at or near 0° C through winter, and below-freezing temperatures can be recorded if the temperature sensor becomes encased in ice (e.g., Figure 17.4, lower panel). Summer temperatures typically range from 10 to 25° C, depending on riparian shading and influences of groundwater and glacier runoff (Figure 17.5), but can reach more than 30° C for poorly shaded streams during extreme summer drought conditions (Quilty et al. 2004). Overlying the annual cycle are variations associated with the passage of frontal weather systems (lasting days to weeks), diurnal (daily) oscillations in daytime versus nighttime air temperatures, storms (hours to days), and microclimatic variation (hours to seconds).

Diurnal variations in British Columbia tend to be relatively small (< 1° C) during winter, especially for interior streams that become filled with snow and ice and remain at or near freezing. In coastal streams, diurnal variation is suppressed in winter by low incident solar radiation and generally higher flows compared with summer. Diurnal variations in summer can range from 2 to 5° C, or even greater (Figure 17.5).

Over large regions, stream temperature broadly follows spatial variations in air temperature, as both variables respond to variations in solar radiation and air mass characteristics. It is also modified by catchment and channel characteristics, such as mean catchment elevation, percent glacier cover, and percent lake cover (Moore 2006). Stream tempera-

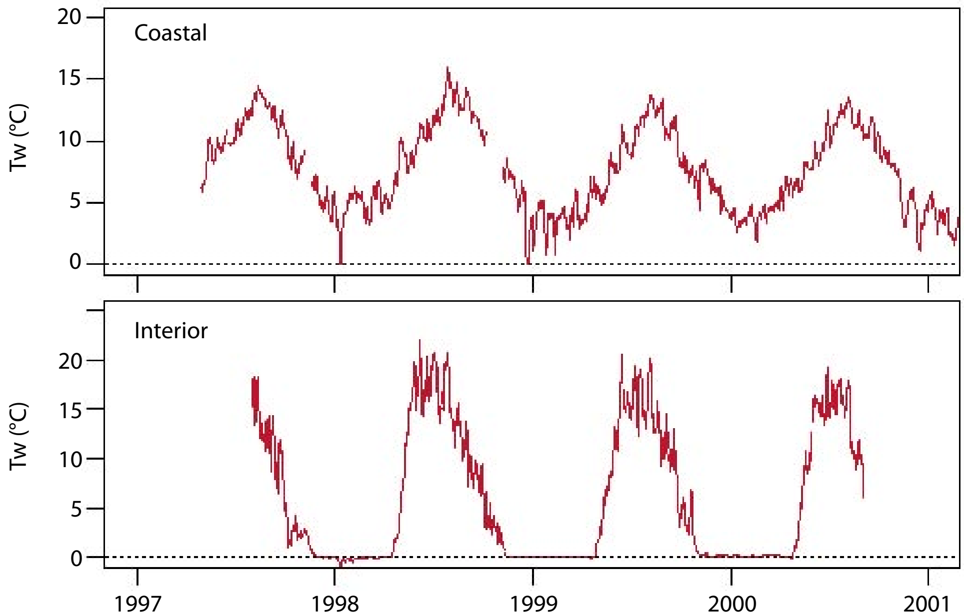

FIGURE 17.4 *Mean daily water temperatures (Tw) for a coastal (upper panel) and an interior stream (lower panel). In the lower panel, the sub-freezing temperatures in early 1998 reflect ice formation around the temperature sensor.*

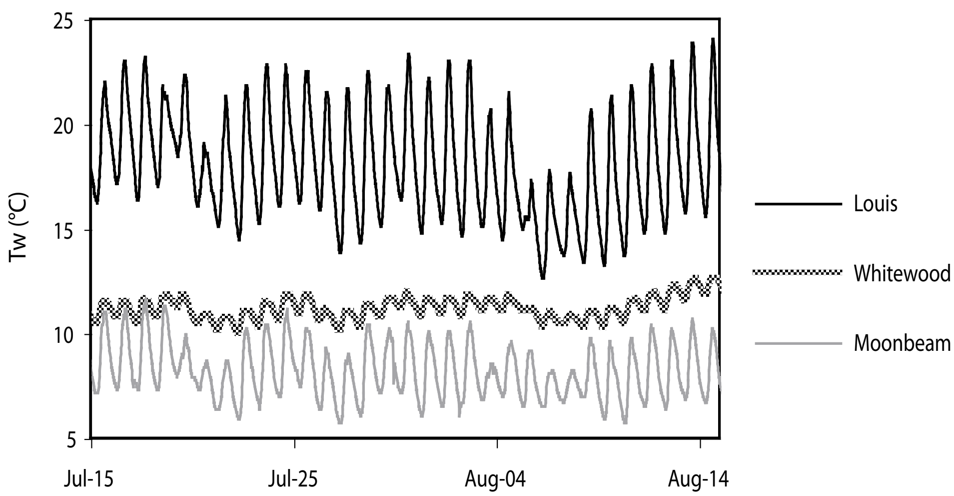

FIGURE 17.5 *Temperature (Tw) patterns for three streams in the North Thompson drainage during summer 2004. The McLure Fire in 2003 heavily disturbed Louis Creek's riparian zone, leaving it poorly shaded. Whitewood Creek is heavily shaded. Moonbeam Creek has significant summer flow contributions from glacier runoff.*

ture tends to increase with distance from the channel head, with headwater streams being generally cooler than larger, downstream reaches. For streams with undisturbed riparian vegetation, diurnal and seasonal variabilities tend to be low for headwater streams, increase for intermediate streams, then decrease for large rivers (Vannote et al. 1980). Local deviations from a dominant downstream warming trend may occur as a result of groundwater inflow, hyporheic exchange, or thermal contrasts between isolated pools and the flowing portion of a stream (Mosley 1983; Bilby 1984; Ebersole et al. 2003a; Story et al. 2003). Localized cool zones, which can offer thermal refugia for cold-water species during high temperatures, are an important aspect of stream habitat (Neilsen et al. 1994; Ebersole 2003b). In addition, a lake, pond, or wetland can produce elevated water temperatures at its outlet, resulting in downstream cooling below for over hundreds of metres, even through cutblocks (Mellina et al. 2002).

Technologies for Measuring Stream Temperature

Most instruments for measuring stream temperature register the direct effects of the thermal agitation of the water molecules, and are often called "kinetic" measurements. Four main types of sensors measure kinetic measurements of stream temperature: (1) thermometers, (2) mechanical thermographs, (3) thermocouples, and (4) thermistors. An alternative technology for kinetic temperature sensing is based on "resistance temperature detectors" (RTDs), which are similar in some ways to thermistors. However, these RTDs are less accurate than thermistors and are not commonly used for water temperature measurement. In addition, stream temperature can be measured using radiometric methods. These record the intensity of infrared radiation emitted by the stream, which is a function of the water surface temperature. Fibre optics technology has been adapted for spatially distributed water temperature measurement (Selker et al. 2006). This approach should see increased application as the technology matures. Characteristics of kinetic and radiometric approaches are summarized below.

Thermometers use the volume changes of a fluid (usually mercury or alcohol) in relation to changing temperature to register the temperature. A field thermometer can be as accurate as ±0.02° C, though it is more typically accurate to about ±0.1° C.

Mechanical thermographs were commonly used for recording water temperature before the advances in electronic data acquisition over the last two decades, but the data are still used, especially where long data records are required. This device records temperature change via its effect on a bimetallic strip. Because the two metals expand differently when heated, temperature changes cause the curvature of the strip to vary. This displacement is translated into the movement of a pen on a recording chart. Resolution is typically about 1° C. The charts must be digitized before analysis, commonly at relatively coarse time intervals such as 3 hours (e.g., Hamel et al. 1997).

Thermocouples are based on the principle that temperature differences along a conductor (e.g., copper) will produce a difference in voltage that is proportional to the temperature difference. A thermocouple is constructed from a special two-conductor wire, with the conductors made from different metals. Various pairings of metals can be employed, but those made from copper and constantan (a copper/nickel alloy) are most appropriate for the typical range of stream temperatures. Thermocouple measurements are typically accurate to about ±0.2° C. Handheld meters are commercially available for taking manual measurements, although most data loggers can make thermocouple-based temperature measurements using a built-in reference thermistor.

Thermistors employ a resistor whose resistance varies with temperature. If the relationship between temperature and resistance is known, then the measured resistance can be converted into temperature. Handheld, thermistor-based instruments are commercially available for taking manual measurements, but thermistors are also connected to data loggers for near-continuous recording. In the last decade, integrated thermistor-logger units capable of submersion in water have become available at a reasonable cost. These can be pre-programmed to specify the logging interval, and have become popular for forest hydrology applications. These instruments have a typical accuracy of about ±0.2° C. Dunham et al. (2005) is a useful reference on measuring stream temperatures with thermistors.

Radiometric measurements can be made using handheld infrared thermometers, airborne sensors, or even sensors on satellite platforms (Torgerson et al. 2001; Rayne and Henderson 2004; Cherkauer et al. 2005; Handcock et al. 2006). The spatial resolution of satellite imagery is too coarse to resolve any but the largest rivers. Airborne systems can resolve medium to large streams, and can give "snapshots" of spatial temperature patterns along extensive reaches, including the locations of local cool zones (thermal refugia) associated with groundwater discharge and inflow of cooler tributaries (Torgerson et al. 1999).

Calibration of Temperature Sensors

Although a temperature sensor is generally reliable and accurate and requires little maintenance, it does require calibration. Thermometers and thermistors should be calibrated annually against an Institute for National Measurement Standards (INMS) calibration thermometer using a temperature-controlled water bath (Wagner et al. 2006). Calibration typically consists of an ice-point reading and calibrations at three to five temperatures within the range of the sensor. When practical, sensors should be checked more frequently using the "ice bucket" method (Dunham et al. 2005), whereby sensors are submerged in an insulated ice bath for 1 hour to verify that readings are 0° C.

In addition to the calibration procedures mentioned above, field meters or thermometers should be used to measure water temperature near the installed sensor during each field visit. After the recorded data have been downloaded, temperatures at the time of field visits can be extracted and compared with the manual measurements as a further calibration check. Such a comparison is particularly valuable where a sensor's calibration may have drifted during the field installation, as it can help to identify the appropriate segments of the data requiring drift corrections.

Verification and Correction of Stream Temperature Data

Before any analysis, data quality must be verified and any errors removed or corrected. Data should be plotted as time series and visually inspected for obvious outliers, such as values that differ substantially from preceding and following values. In many cases, the observations at the beginning and end of each data set need to be removed because the sensor would have been measuring air temperature while being programmed or downloaded in the office or at the field site. Similarly, any observations that were recorded when the water dropped below the sensor level (e.g., summer drought low flows, "dewatering") need to be removed. These measurements are usually relatively obvious, with sudden and substantial increases in daily oscillations and daily maximum values (Figure 17.6). When examining data to locate errors, it is helpful to compare stream temperature records with other nearby records, such as those from upstream or downstream stations, and local or regional climate stations.

When appropriate for project objectives, small data gaps can often be filled by using linear interpolation or modelling techniques. As a general guideline, interpolation should be used only on gaps that are less than 2 hours long, which is often sufficient for filling gaps created by removing air temperature data recorded during downloading. Modelling techniques can be used for longer gaps (hours to days); however, modelled data must be interpreted cautiously. Gap filling with models is possible when surrogate data, such as stream temperature from upstream or downstream sensors or nearby watersheds, are available. Typically, a simple linear or multiple linear regression model is developed using several weeks of data immediately before and after the gap. Air temperature is also used as a surrogate, although linear models may be unsuitable because of nonlinearities at high (> 25° C) and low (freezing) temperatures (Webb et al. 2003). In all cases, detailed notes on gap-filling instances, methods, and rationale must be produced and kept with the data.

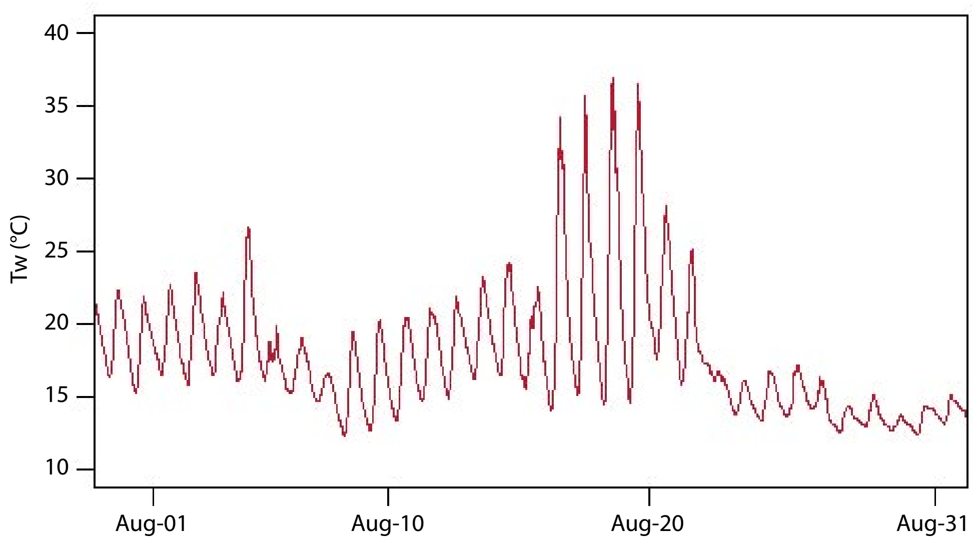

FIGURE 17.6 *Stream temperatures (Tw) before, during, and following a dewatering event, which began August 16 and ended August 22.*

Recommendations for Monitoring Stream Temperature

The following general recommendations are based on experiences in measuring stream temperature at sites throughout British Columbia. Specific implementation may need to be varied to suit conditions at individual sites and (or) project objectives.

Sensor selection and programming

Some manufacturers of temperature loggers, such as Vemco and Onset, produce units with different temperature ranges. It is important to purchase models that cover the range of stream temperatures that can occur within British Columbia. Ideally, a logger should record temperatures ranging from below 0° C and to at least 35° C.

Data loggers can be programmed to record either the individual measurements or process the data and output summary statistics (e.g., mean, maximum, minimum) for a time interval. When the immediate need is only for mean daily temperatures, it may seem simplest to program a logger to generate daily summaries. However, given the high temporal variability of stream temperatures, and the relative ease of use and reasonable costs of thermistors, high frequency monitoring (hourly or every 10–20 min) is now preferred, even if the data are only used to calculate daily means. This approach allows data to be used for various purposes beyond those for which the data may have been originally collected. This approach also allows field measurements of temperature using a standard instrument to be associated with a specific recorded value for comparison and calibration, as described earlier. Examination of the time series can also be valuable for interpreting data logger malfunctions or dewatering events (Figure 17.6).

Sensor installation and placement

A sensor should be shielded from solar radiation to avoid any possibility of anomalous heating, particularly during low flow periods, when low-flow velocities and high sun angles can cause the sensor temperature to rise above ambient water temperature. Several investigators have placed sensors within short lengths (10–20 cm) of pipe. Emplacement in these shields also keeps the sensors out of direct contact with the streambed, which may be cooler or warmer than ambient stream temperature in groundwater discharge zones, depending on season and time of day.

A sensor needs to be placed where it will be protected from natural disturbances, such as substrate movement and debris during storm flows, and where it can be relocated easily. In small streams with low stream power, rebar hammered vertically into the bed can suitably anchor a sensor. In larger streams, a sensor is usually attached to a suitable weight that, in turn, is leashed to an anchor point. Suitable weights include sand bags, blocks of concrete, exercising dumbbells, or other objects appropriate to a specific site. Heavy-duty clothesline is often an appropriate material for "leashing" thermistors to a streamside tree or other anchor. The anchor should ideally be fixed firmly in place, and not be movable during high flow. For example, large logs along the streambank may be stable at lower flows, but are prone to being swept away during high flows. Despite the best efforts, thermistor loss due to burial or significant channel erosion is always possible. For example, the second author installed a network of submersible temperature loggers in the southern Coast Mountains in summer 2003, and lost several during the October 2003 floods. One temperature logger ended up buried under 2 m of gravel, and another was lost when significant bank erosion swept away the mature tree to which the instrument was leashed.

Sensor placement can be challenging, especially in streams with wide ranges of flow. The sensor should be placed where it will not become dewatered but will still experience water flow (i.e., not in stagnant pools). For streams that have not been viewed at a range of flows, it can be difficult to anticipate the patterns of depth and velocity during extreme conditions.

During installation, detailed hand-drawn maps and notes must be made and photos taken so that sensors can be relocated during various seasons and flows when sites can look quite different. Even though current temperature loggers may have sufficient memory to be left unattended for months, frequent field checks are recommended to ensure that the sensor is not lost, exposed to air, or placed in an isolated pool at low flows.

Other comments

Streams that freeze or become covered with snow and ice present a range of challenges. It may be difficult to locate a temperature logger within a snow-filled channel or to remove it from under a thick ice cover. Additional problems may occur in larger streams, where channel ice can remain intact through the early spring melt. In such cases, ice may be moved downstream with the flow, resulting in movement or loss of the instrument. Ideally, temperature loggers at such sites should be visited and downloaded in autumn to avoid possible data loss.

Another important issue is spatial heterogeneity of stream temperature within a reach, which tends to be greatest during periods of high stream temperature. Stream temperature variability should be measured with a manual instrument on warm summer days to assess how representative a monitoring site is relative to other locations within the reach.

Temperature loggers can collect tens of thousands of measurements each per year, making organization and storing of the data a challenge and data archiving paramount. Ideally, all data should be organized and stored in a relational database. At a minimum, each download file should be fully documented with metadata, such as site and deployment information and field notes, and be stored in at least two secure locations.

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Biological Water Quality – Biological Measures

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BIOLOGICAL MEASURES

Biological measures at all levels of integration from genetics and populations to communities and ecosystems can provide useful information to assay the influences on natural systems of land use (local and regional), climate, and other sources of variation. Population and community measures for fish and aquatic invertebrates are discussed in the next subsection. In this subsection, measures of ecosystem processes and metrics for other taxonomic groups beyond fish and invertebrates are briefly considered. There are many types and uses of biological measures (enough to justify their own compendium). Often biological measures are used as response variables in before-and-after "treatment" comparisons, including those that also have concurrent spatial controls (i.e., other catchments with no manipulation at the time of the treatment). Ecosystem measures are used across gradients of land use, from reference (unmanaged) to highly perturbed watersheds. Biological measures are also used to assess the effects of particular treatments, using a set of reference sites expected to represent the "population" of untreated streams. In general, ecosystem processes are more comparable across the landscape than specific components of ecosystems, such as species, which have a more limited range.

The wide variety of biological measures used in freshwater include descriptors of the biological communities, including the productivity, standing stocks, and relative abundance, as well as diversity of bacteria, algae, protozoa, fungi, and animals. The composition of some taxonomic groups in a water body, for instance bacteria and protozoa, might also provide useful information on ecosystem conditions; however, the methods for obtaining these measures usually require more specialized expertise and equipment. Other measures used to describe ecosystem functions and rates of processes, are the dynamics of organic matter input or export (e.g., leaf litter, dissolved organic matter in groundwater) and primary production, the rates of biofilm production, measures of whole system respiration, and organic matter decomposition rates.

In freshwater, biologically available energy comes from two sources: (1) allochthonous matter, or organic matter (also called detritus) produced outside the system; and (2) autochthonous matter, or organic matter produced within the system (mostly by algae). Thus, measures of these two types of energy yield important information about biological productivity and shifts in predominance of energy sources. Allochthonous organic matter is by far the most important (Kiffney et al. 2000; Richardson et al. 2005) in terms of quantity. The rate of retention of this material within stream reaches and its rates of decomposition are known to be sensitive indicators of stream condition or "health" (Gessner and Chauvet 2002).

Biological Measurement Methods

A wide variety of methods are available for sampling many of the biological measures, depending on the question at hand and the nature of the system under study (Table 17.7). Some methods are applied to streams of all sizes, whereas other measures (e.g., fluxes of organic matter) are more tractable in smaller systems. Among the best sources of general information on many of these methods are the compilations of Hauer and Lamberti (2006) and Graça et al. (2005).

Algae can be measured, either for biomass (measured as the photosynthetic pigment chlorophyll *a*) or taxonomic composition. Samples can be collected from natural rocks or artificial substrates (unglazed ceramic tiles or microscope slides). Typically, a sample from a known surface area is scraped or brushed from the substrate (e.g., Kiffney et al. 2003, 2004). Samples for biomass are then determined either by extraction of photosynthetic pigments (e.g., chlorophyll *a*) followed by fluorometric or spectrophotometric estimation, or by filtration to weigh total

TABLE 17.7 *Biological measurement methods*

Measures	What it measures	Reference[a]
Algae—abundance or concentration	Estimates of net primary production (a key basal resource)	Hauer and Lamberti 2006
Algae composition	Community structure and nutrient status	Hauer and Lamberti 2006
Fungi	Community structure and biomass	Dang et al. 2005; Graça et al. 2005
Biofilms	DOC concentrations, etc.	Hauer and Lamberti 2006
Organic matter	Energy source available to the biological communities	Kiffney et al. 2000; Tiegs et al. 2007
Whole-system respiration	Net integration of all biological process rates	Jones and Mulholland 1998; Carpenter et al. 2005
Decomposition rates	A key function in aquatic food webs, sensitive to populations of decomposers	Gessner and Chauvet 2002; Hauer and Lamberti 2006

a See also British Columbia Resources Information Standards Committee documents at http://archive.ilmb.gov.bc.ca/risc/pubs/aquatic/.

organic matter of the biofilm (measures all organic matter including algae, bacteria, etc.) biomass directly. Methods to estimate the composition are varied, but usually include some cleaning of the sample and settling into a chamber for examination by microscope where taxa are identified and enumerated (e.g., Hauer and Lamberti 2006).

Fungi can be sampled on leaves placed in the stream and used as a substrate, or from natural substrates. Determination of the actual species composition requires microscopic examination of fungal structures, or extraction of ergosterol (a specific component of fungal cell walls) to estimate biomass (see Dangles et al. 2004; Graça et al. 2005). Fungi will also grow on cotton strips, which can be used as a standardized substrate.

Organic matter dynamics and decomposition rates are increasingly used as an indicator of system conditions. A degraded stream is often less retentive (e.g., fewer pieces of large wood or complex bed configurations that trap leaf matter), and it may also have lower input rates of organic matter because of canopy removal. Decomposition rates of existing organic matter increase with increasing temperatures (Richardson 1992) or nutrients (Greenwood et al. 2007). Decomposition rates may also decrease (accounting for temperature) if particular species, such as alder, are reduced in relative abundance (Dangles et al. 2004). Bacterial respiration can be measured, as a component of biofilms, but it is complicated and usually involves laboratory assays using tritiated leucine or thymidine (McArthur and Richardson 2002). Finally, as an integrated system measure, whole-system respiration can be measured using diurnal variation in oxygen concentrations, correcting for rates of exchange with the atmosphere (Jones and Mulholland 1998).

Limitations, Applications, and Interpretations of Biological Measures

Some of the biological methods discussed in this subsection are used in many parts of the world in an operational way and many are still under development. Relative to measures of fish and aquatic invertebrates, these measures are not as commonly used, and estimates of some of these kinds of measures are scarce for British Columbia streams (e.g., Richardson and Milner 2005).

Appropriate study designs for streams can be difficult: for most scientific and management questions, streams are the unit of replication. In some cases, channel units or experimental units (e.g., cages, leaf packs, flumes) are the study unit, depending on the question. Difficulties can arise because of the sampling scales for using streams (or catchments) as study units, the large amount of background variation among streams, and variation through time. An individual stream is a unit of replication—and no matter how many times it is sampled, it is still one unit. Comparing a single stream before versus after treatment is possible statistically, but inference beyond this stream is not possible. Paired-catchment approaches, in which one stream is retained as a control, offer more ability to statistically analyze data using randomized intervention analysis (e.g., Carpenter et al. 1989) and potentially correct for serial autocorrelation in the data (lack of independence); however, this approach is also fraught with comparability issues, as is often noted in hydrological studies. The strongest comparison possible, if feasible, is to have before–after comparisons, with controls, and many replicate streams.

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Biological Water Quality – Fish and Aquatic Invertebrates

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FISH AND AQUATIC INVERTEBRATES

Fish and aquatic invertebrates are sampled in streams, lakes, and wetlands as an integrative biological measure of the status of the ecosystem. These taxa are also sampled to determine the status of particular species, or subsets of the biological community. These taxonomic groups are well represented in British Columbia with about 72 species of freshwater fish (depending on inclusion of unusual forms like stickleback pairs or other unique forms; McPhail 2007) and likely over 1000 species of freshwater invertebrates (> 80 dragonflies and damselflies alone). These species have life cycles spanning months to years, and as such integrate various impacts over time that are reflected in population abundances or size structure, and in the composition of the community. Such measures of response can include changes in individual (e.g., growth, reproduction, or survival), population (abundance, distribution), or community characteristics (e.g., composition, structure, diversity). As a result, such variables are sometimes used as response measures to assess changes in freshwater systems caused by land use effects. In the case of fish, measures of potential fish habitat are commonly used as a proxy for actual fish populations, given the effort and uncertainty associated with actual sampling of fish. For general references, refer to the sources listed in Table 17.8.

Fish and Aquatic Invertebrate Measures

Fish, most typically salmonids, are commonly sampled as a response measure to land use, such as forest practices (e.g., Meehan [editor] 1991; Northcote and Hartman 2004; De Groot et al. 2007). The relative abundance, species composition, growth rates, age structure, survival, and timing of migration of fish are all used as response measures, given appropriate points of reference (i.e., "control" sites or data from before management). Sampling fish abundance requires many assumptions about the species "catchability" and movement patterns. Often densities decrease in a self-thinning manner as cohorts of similarly aged fish increase in age and individual size (creating an increasing demand for food and space). Individual fish can be tagged with various markers for later identification of individuals, and are also equipped with radio-transmitters for use in tracking the habitat use and movements of individuals. Invertebrates are used as indicators by using particular taxa, or more often as portrayed by shifts in community structure—known as benthic biomonitoring (Reynoldson et al. 2001; Bailey et al. 2004).

Fish and Aquatic Invertebrate Measurement Methods

Fish are collected or observed in many ways, depending on the particular question (see Table 17.8). At the catchment scale, fish are trapped using fish fences (block entire flow to stop fish and direct them into narrow traps) or screw traps (sample "out-migrating" fish from the flow). Both of these methods are expensive and thus are limited in use. At the channel-unit scale (1–10 m), seine nets, Gee ("minnow") traps, or electrofishing are used. Fish are also sampled within a habitat unit and even at the reach scale (approximately 100–1000 m in length) by snorkelling and recording the number, relative size, and species of individuals seen as an observer either floats downstream or moves upstream. Fish are marked in various ways, with the method depending on whether the fish will be repeatedly sampled or recaptured once during its life as it returns to freshwater from the ocean. In the latter case, coded wire tags inserted into the fish's head can be retrieved later, but only upon its death. Other tags, such as passive integrated transponders (RFID tags),[3] visual implant tags, and elastomer dye marks, identify individuals

3 Radio Frequency Identification (RFID) is an automatic identification method that relies on storing and remotely retrieving data using devices called RFID tags or transponders.

TABLE 17.8 *Fish and aquatic invertebrate measurement methods*

Measures	What it measures	Reference [a]
Fish abundances	Productivity; survival and reproduction	Murphy and Willis (editors) 1996
Fish age/size structure	Demography and age-specific, time-specific impacts	Murphy and Willis (editors) 1996
Fish habitat	Habitat availability and suitability	Bain and Stevenson 1999
Invertebrate abundance	Productivity of streams	Merritt and Cummins 2007
Invertebrate composition	Changes in community structure related to food resources, toxins, temperature, or other changes to the aquatic system	Reynoldson et al. 2001; Bailey et al. 2004

a See also British Columbia Resources Information Standards Committee documents at http://archive.ilmb.gov.bc.ca/risc/pubs/aquatic/.

that are subsequently retrapped. For visual observation, tags such as Floy tags or even coloured beads are used. Fish numbers are estimated using depletion estimates (i.e., blocking a short reach of stream and making several passes of the reach removing fish each time). As the numbers of fish are depleted in the blocked reach, the numbers of new individuals trapped in each pass will diminish and yield an asymptotic estimate of the actual numbers. Another method taking advantage of marking individuals is some form of capture–mark–recapture estimate for which there are many types of estimation algorithms (see Krebs 1999).

Aquatic invertebrates are typically sampled quantitatively (density) or qualitatively (composition, relative abundance). Quantitative sampling has various samplers, the two most common being the Surber sampler or Hess sampler (Merritt and Cummins 2007). For qualitative estimates, sampling is typically accomplished using a D-frame net (sometimes called a dip net). A method that is rarely used for standard sampling any longer is the use of substrate baskets, in which a volume of similarly sized mineral particles are placed into a cage of wire or plastic mesh and collected some time later allowing for colonization by benthic invertebrates. In some studies, the measurement of "drift" rate of stream invertebrates is included as a flux of food for stream fishes (Romaniszyn et al. 2007). Finally, if specific identifications are needed, or if biomass of emerging insects is of interest, it is possible to use emergence cages for the adult stages of aquatic insects, which constitute a preponderant component of the benthic fauna.

Limitations, Applications, and Interpretations of Fish and Aquatic Invertebrate Measurement Methods

Sampling fish can be challenging, especially given that many species migrate to alternate habitats, including lakes, estuaries, and the ocean at various times in their lives, and the timing of those migrations, and the ages of fish doing so, may vary depending on productivity, temperature, and other habitat factors. Therefore, changes in numbers within a site alone are usually insufficient to lead to a conclusion about habitat condition unless these data are collected across years. Typically, one needs to have more detailed information, or appropriate control catchments, to adequately account for climate and other life history responses. Most appropriately, it is necessary to have control or reference populations for comparison, and better yet to have before-and-after time-series data (e.g., De Groot et al. 2007). In addition, identifying juvenile fish can be difficult and requires training and experience; however, snorkelling is used across habitat units, stream sizes, and seasons, making comparisons possible.

If done improperly, electrofishing is detrimental to fish, especially in the very low-conductivity water of coastal British Columbia, and is difficult in large fast-flowing rivers. As a consequence, electrofishing in British Columbia requires certification. Gee traps can also be detrimental if these traps are lost or left in a stream unintentionally for an extended period of time. Gee traps may also trap unequally sized fish, often leading to the larger fish eating the smaller individual. Studies conflict over whether tagging fish alters their behaviour, slows them down, or makes them more apparent to predators, but each of these factors could bias studies if marked fish differ in any way from the unmarked fish they are intended to represent. Nevertheless, trapping fish allows one to measure and weigh fish and enables comparisons in biomass and growth rates among sites.

The expected values for measures of productivity or composition of fish or invertebrate assemblages differ by region of the province and by season. One of the first points of separation is the difference between coastal and interior regions, which have largely distinct hydrological regimes. The Coast and Interior also differ in faunal composition (e.g., Reece and Richardson 2000; McPhail 2007), underlying geology (affecting hydrology, geomorphology, and chemistry), and surrounding vegetation communities. Thus, most of these measures need to be calibrated for particular ecoregions (or finer) within the province.

Biomonitoring has been adopted by management agencies in many jurisdictions, and is under development in British Columbia. Most commonly, benthic macroinvertebrates are used for biomonitoring, in part because of the many species and range of sensitivities to impacts (Bailey et al. 2004). Biomonitoring can also be done using fish, algae, and even macrophytes. Two major groups of biomonitoring tools are widely used: (1) the Benthic Index of Biotic Integrity (B-IBI) (Herlihy et al. 2005), and (2) the Reference Condition Approach (RCA) (Bailey et al. 2004). Environment Canada has sponsored development of an RCA-based approach in British Columbia along with an online data storage and retrieval system known as CABIN (Canadian Aquatic Biomonitoring Network). Invertebrates are also used in bioaccumulation studies to assess long-term exposure to fat-soluble contaminants. Another tool for assessing the condition of freshwaters is the Indicator Species Approach developed by Dufrene and Legendre (1997). This approach contrasts the magnitude of effect sizes (abundances or biomass) between species from reference versus potentially perturbed sites.

In general, biomonitoring tools require some form of regional calibration against sites (streams) considered to be in "good" condition (i.e., reference sites against which perturbed sites are contrasted). A need also exists to calibrate for geomorphic variation (widths, gradients, channel forms) and geology. Each of these requires that a specific model take place within a class of stream and within a given ecoregion, although extrapolations are possible, and evidence is mounting that broadly applicable models are possible (Reynoldson et al. 2001; Bailey et al. 2004); however, incorporating additional sources of variation typically make the models less sensitive to environmental change.

One can examine changes in composition of biological communities in terms of diversity, age composition, size structure, or energy flows (trophic structure) (e.g. Gjerløv and Richardson 2004). These additional measures can yield other insights into why communities might change in response to alteration of stream condition, and may be diagnostic. The biomonitoring tools rely on such changes. By themselves, these tools indicate deviation but not a potential diagnosis, although that is developing.

As noted previously, one of the biggest challenges with studies of biological responses to land use is the frequent absence of clear management objectives and quantitative targets for the work (Villard and Jonsson [editors] 2008). Equally important is the common failure to follow a rigorous study design that allows for proper statistical analysis and scientific rigour. The limitations can also be financial (funding for several years and many sites) or urgency (answers were needed "yesterday").

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Geomorphology – Sediment Source Mapping

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SEDIMENT SOURCE MAPPING

Sediment source inventories are useful for research on watershed sediment budgets, and for applied purposes such as assessing the impact of forest management activities on a watershed, or investigating the causes of stream channel changes during major hydrological events.

Watershed sediment yields vary greatly in different hydrologic regions of British Columbia, and also vary greatly on a local scale in response to site-specific sediment sources within watersheds. Typically, most sediment in a small watershed originates from a few discrete sources, such as landslides, debris flows, or glaciers. Most forested areas in British Columbia have relatively low sediment yields. In a forest management context, a need often exists to estimate the amount of sediment originating from natural and development-related sources. Typical natural sediment sources in forested watersheds without glaciers include:

- bank erosion (usually low unless a stream is incised into glacial deposits);
- tree fall adjacent to stream channels;
- debris flows originating in alpine areas or chronically unstable bedrock;
- slump-earthflows in valley-bottom glacial deposits; and
- snow avalanche debris.

In forested watersheds lacking large natural sediment source features, forest development has been shown to greatly increase sediment yield. Typical development-related sediment sources include:

- erosion from forest roads and skid trails;
- undercutting, or washouts of roads bordering streams;
- landslides originating from forest roads and logged areas;
- failure of, or erosion adjacent to, culverts and bridges; and
- dispersed erosion from recently logged areas (usually an insignificant source).

Sediment source inventories can be conducted at three general levels of detail.

1. **Simple inventory of sediment source features.** The product is typically a map showing the location of discrete features, such as landslides, with perhaps a simple classification based on size and degree of activity. It can be based on air photo interpretation with a field reconnaissance, or it can be derived from an existing terrain map. This type of inventory is useful for initial investigations of whether forest management practices in a watershed pose a problem, and the relative significance of natural and development-related sediment sources.[4] It is also useful for prioritizing watershed rehabilitation activities. Some procedures for conducting inventories were developed for the Watershed Restoration Program from 1994 to 2001. However, this type of inventory does not quantitatively measure the volume of sediment entering a stream.
2. **Semi-quantitative sediment source inventory.** At this level, the volume of sediment produced by each sediment source feature and its connectivity with the stream channel system is estimated. For example, each landslide in the watershed, or a representative selection if many landslides occurred, is visited in the field; its dimensions and the proportion of its volume that has entered the stream channel are measured or estimated. Another example of this type of inventory is road erosion surveys (Henderson and Toews 2001), discussed below. These sediment source inventories are useful in sediment budget studies, in which sediment sources, storage, and output in a watershed are quantified. This type of inventory is also likely to be useful for enforcement under the *Forest and Range Practices Act*; for example, to demonstrate that a development-related landslide has caused a "material adverse effect" on a stream. Sediment source inventories of this type are likely to produce a reliable order of magnitude or better estimate of the volume of sediment contributed to a stream in a particular year.
3. **Measurement of individual sediment sources.** Examples of this type of inventory include measurement of hillslope erosion, road surface erosion, and road culvert sediment yield using various types of sediment traps, catch basins, and samplers (Jordan and Commandeur 1998). For example, to measure the sediment yield of a segment of road drained by a culvert that enters a gully, a trap can be constructed below the culvert in the gully to retain material of bed load size and an automatic pump sampler can be used to sample suspended sediment. Measurements of this type are useful for research projects, but are usually impractical for watershed sediment monitoring because of the high cost and the labour required. The results can be reasonably accurate, but may not be representative, as it is usually not feasible to measure more than a small sample of the sediment sources in a watershed.

4 Alcock, J. 2005. Reconnaissance hydrological overview, Blaeberry River Watershed, north of Golden, B.C. B.C. Min. For., Columbia For. Distr., Revelstoke, B.C.

Some authors (Reid and Dunne 1996; Jordan 2001) report erosion from forest roads as a very significant source resulting from forest development. This topic is covered in greater detail in Chapter 9 ("Forest Management Effects on Hillslope Processes"). A method for estimating sediment contributions from road erosion has been developed for sediment budget studies in southeastern British Columbia (Henderson and Toews 2001; Jordan 2001, 2006). Similar methods have been developed for studies of road erosion and sedimentation on the coast (Carson and Younie 2003).

First, the road network in the watershed is divided into segments, with each segment having reasonably uniform properties such as slope, surficial material, proximity to streams, and evidence of erosion. For each road segment, the dimensions of rills and other erosion features are measured or estimated to calculate the source erosion from the road surface, ditches, cuts, and fills. The volume of fine sediment produced at the site is estimated, based on the proportion of fine sand, silt, and clay in the eroded material. The connectivity between the site and the stream is then rated, to estimate the amount of sediment that reaches the stream channel. Measurement of source erosion is reasonably accurate if the survey is done soon after a spring runoff or rainstorm event, when evidence of erosion is fresh; however, estimation of the connectivity is subjective and includes a high component of operator judgement. It is based mainly on observing field evidence of flow pathways between road culverts and the streams. Because of the potential error and poor repeatability in estimating this parameter, sediment delivery data from erosion sources is very approximate, and should be considered an order of magnitude estimate only.

This method has been used successfully for relatively low-use forest roads in the southern Interior, which are not kept open in winter and for which the main erosion event each year is the snowmelt freshet. In regions dominated by rainfall, a survey must be completed after each significant rain event to estimate total annual erosion. On heavily used forest roads that are frequently graded and are actively used for log hauling, the method is difficult to apply, as grading and heavy truck traffic obscure evidence of surface erosion and introduce additional sediment.

Beaudry and Associates developed an operational field tool to estimate sediment production from forested roads in the northern Interior of British Columbia, focussing on stream crossings and how these might be expected to respond to rainfall events.[5] This Stream Crossing Quality Index (SCQI) has been used successfully by licensees in the Interior to judge performance in maintaining water quality.

With the implementation of the Forest and Range Evaluation Program (FREP), a methodology has been developed (see Carson et al. 2009) that incorporates features of the work done by Beaudry and Associates in the interior and Carson Land Resource Management Ltd. on the coast. The procedure provides a means to quantify fine sediment production from both mass wasting and surface erosion associated with all forestry and range activities, including erosion from roads and logged areas, slope failures, and disturbance by livestock.

In general, experience has shown that sediment production from forest roads is greatest in the first year or two following construction, and declines thereafter as the road surface, cuts, and ditches stabilize. Cutslopes and ditches tend to produce the most sediment, followed by the road surface. Fillslopes produce relatively little sediment unless these encroach on stream channels. On older roads, sediment production increases greatly with increased use by industrial traffic, and with more frequent grading.

The method above can be applied at a detailed level, with the road system divided into many short segments, and with measurements taken several times per year. This will reasonably accurately estimate total sediment production from roads in a watershed. For many purposes, however, it can be applied at a less intensive level, with detailed measurements made on only a few representative segments, and erosion from the rest of the road system estimated using a simple classification system (Table 17.9).

5 Beaudry, P. and Associates. 2006. Stream crossing quality index: a sustainable forest management indicator of maintenance of water quality. Field Manual, Ver. 20. Report prepared for Canadian Forest Products Ltd. Unpubl. report.

TABLE 17.9 *Classification of road surface erosion used in southeastern British Columbia. Based on tables in Henderson and Toews (2001) and the Interior Watershed Assessment Procedure (B.C. Ministry of Forests 2001).*

Class	Median sediment production (m^3/km)	Range of sediment production (m^3/km)	Typical rill dimensions (cm)	Visual description
1	0.1	< 0.3	10 × 0.1	Almost unnoticeable rills
2	1	0.3–3	10 × 1	Light erosion (typical of well armoured low-use roads)
3	10	3–30	50 × 2	Moderate erosion (typical of erodible materials, average maintenance, high-use roads)
4	100	30–300	100 × 10	Severe erosion, access difficult with a 4WD but not impassable
5	1000	300–3000	200 × 50	Severe gullying, impassable but repairable
6	10 000	> 3000	1000 × 100	Total washout, road gone

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Geomorphology – Channel Measures

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CHANNEL MEASURES

Numerous measurement techniques have been developed to address both the temporal and spatial aspects of river and stream channel forms and processes. As a result, these techniques cover a huge range of issues including differing levels of complexity, detail, and cost to undertake. Kondolf and Piégay (2003) considered the range of measurement techniques and stated that "…as do all scientists, fluvial geomorphologists employ tools in their research, but the range of tools is probably broader in this field than others because of its position on the intersection of geology, geography, and river engineering." Their large volume, titled *Tools in Fluvial Geomorphology* (Kondolf and Piégay 2003), covers the topic of channel measures in exhaustive detail; this reference includes specific details and summary tables of most techniques available in fluvial geomorphology. Readers interested in channel measures should refer to the Kondolf and Piégay reference because it covers all aspects far more comprehensively than is possible in this subsection.

It is difficult to compile a short list of channel measures because the success of any study will be determined by how clearly the purpose of the study is articulated and the appropriate methods selected that logically follow from the questions posed (Kondolf et al. 2003b). Kondolf et al. (2003b) stated that when selecting sampling methods, one needs to identify what, why, and to what level of confidence the collected data are to be used. Two examples illustrate these points. A common measure in stream investigations is the determination of channel gradient. A relatively uncomplicated attribute such as stream channel slope can be measured using many different techniques. At one end of complexity, a simple and inexpensive handheld inclinometer can be used. At the other end of the spectrum, very expensive total station survey or global positioning stations can be used. Technique selection will depend on whether the surface is a uniform plane or is characterized by various sediment and debris storage elements, the length of channel to be averaged, and the specific features to govern survey breaks. With each measuring approach, a very different level of training is required and different costs incurred. These sampling decisions are common to most (or all) channel measurement problems.

Clearly, the overriding determinant underlying the channel measurement technique selected depends on the objective of the work. For example, a common request is to characterize channel sediment patterns; however, to sort out what is really required is not simple. The measurement technique used to characterize the surface sediment texture at one point in space, and at one time, will be very different than if an attempt is made to determine trends in the change in surface bed texture over time and (or) along a stream reach. This situation gets progressively more complex when the desired results include differentiation between surface and subsurface textures.

In this subsection, we will briefly highlight the range of measurement techniques commonly used for stream channels, including morphology, scour, sediment texture, in-stream large woody debris, and canopy cover for shade. See Kondolf and Piégay (2003) for a primarily academic review of techniques, and Timber-Fish-Wildlife (1994), B.C. Ministry of Forests and B.C. Ministry of Environment (1996b), Newbury and Gaboury (1993), and Tripp et al. (2009) for practical field applications.

Several common channel measurement methods are included in Table 17.10. The techniques are described fully in the accompanying references.

Common Limitations of Channel Measures

Several problems are common to many of the methods listed above. Many measures are stage/discharge dependent (feature will have different dimensions when the stream is at different discharge levels), including measurement of pool, riffle and run dimensions, area of bars, and islands debris accumulations, etc. This can be a problem when trying to compare a stream feature over time or when different surveyors are used. The *Channel Assessment Procedure Guidebook* (B.C. Ministry of Forests and B.C. Ministry of Environment 1996b) specifically addresses this issue.

TABLE 17.10 *Channel measurement methods*

Attribute	Sources/materials	Typical use/measure[a]	Reference
Morphology	1:50 000 aerial photograph, stereoscope, photogrammetric tools	Restricted to channels with W_b >30 m, interpretation commonly channel pattern, sediment supply, channel stability	Kellerhals et al. 1976; Gilvear and Bryant 2003; Kondolf et al. 2003a, 2003b; Simon and Castro 2003
	Large-scale aerial photographs, stereoscope, photogrammetric tools	Restricted to channels with W_b >20 m (1:20 000) and W_b >10 m (1:5000), interpretation commonly channel pattern, sediment supply, channel stability	B.C. Ministry of Forests and B.C. Ministry of Environment 1996a
	1:250 aerial photograph, stereoscope, photogrammetric tools	Detailed bed and bank morphology, surface sediment characteristics, large woody debris arrangement, and riparian condition	Ham and Hogan 1998
	1:5000 and smaller-scale topographic maps	Longitudinal profiles, large river channel pattern, drainage areas, hillslope coupling, and stream network connectivity	Leopold et al. 1964; Newbury and Gaboury 1993
Channel type	Field inspections	Based on channel dimensions (L_l, W_S, W_b, D_S, db, S, Q_b), pattern, and shape	Church 1992; Timber-Fish-Wildlife 1994; B.C. Ministry of Forests and B.C. Ministry of Environment 1996b; Hogan and Bird 1998; Halwas and Church 2002; Kondolf et al. 2003b
Bedrock	Field inspections		B.C. Ministry of Forests and B.C. Ministry of Environment 1996b; Kondolf et al. 2003b
Step-pool	Field inspections	Step composition, arrangement and dimensions	Grant et al. 1990; Kondolf et al. 2003b; Church and Zimmerman 2007
Rapids/run	Field inspections		B.C. Ministry of Forests and B.C. Ministry of Environment 1996b, Kondolf et al. 2003b
Cascade	Field inspections		B.C. Ministry of Forests and B.C. Ministry of Environment 1998b; Kondolf et al. 2003b
Riffle-pool	Field inspections	Riffle type/pool type	B.C. Ministry of Forests and B.C. Ministry of Environment 1998b; Kondolf et al. 2003b
Sand bed and finer	Field inspections		Kellerhals et al. 1976; Church 1992
Bar type/ stability/extent	Field inspections		Church and Jones 1982
Sediment texture Bed features	Field and remote sensing		Ham and Hogan 1998; Bunte and Abt 2001; Kondolf et al. 2003b
Surface	Tape/calipers/template	D_S, D_{50}, D_{84}, D_{95}, sorting, shape, armour ratios	Wolman 1954; Church 1998; Graham et al. 2005
	Grid		Kellerhals and Bray 1971
	Photographic		Graham et al. 2005

TABLE 17.10 *Continued*

Attribute	Sources/materials	Typical use/measure [a]	Reference
Subsurface	Sieve/sample splits	D_{sub}, D_{50}, D_{84}, D_{95}, sorting, shape, armour ratios	
Aquatic	McNeil, freeze cores		
	Distributed bulk		Wolcott and Church 1991
Bed scour/fill	Scour chains/surveys (XS/LP-DEM)/tracers	Tapes, survey stations/tracer detectors	Hassan and Ergenzinger 2003
Large woody debris	Tapes/compass/survey equipment/aerial photos	L_l, D_l (× 2), frequency, shape, state, function, source, pieces, mechanism/distance	Timber-Fish-Wildlife 1994; Hassan et al. 2005
	Jams		Hogan and Bird 1998
	Survey rod, level, compass, level, shovel		
	Composition	Material, thickness, bedding	Hogan and Bird 1998
Banks			
Shade	Clinometer, spherical convex densiometer, hemispherical image	% cover/open	Kelley and Krueger 2005
Riparian	Properly functioning condition		Prichard 1998; Tripp et al. 2009
	Shape	U_C, O_H, verticals, sloping	

a W_b: channel bankfull width; Q_b: bankfull streamflow discharge; S: channel slope; D_s: diameter of b-axis, surface sediment (not subsurface bulk, D_{sub}); db: bankfull depth; D_{50}: of a sediment sample, 50% of which is finer than D_{50} (mm, o); D_{84}, D_{95}: as above L_l: length of large woody debris piece; D_l: diameter of large woody debris piece; U_C: undercut bank; O_H: overhanging bank; W_s: water surface.

Furthermore, many features such as channel bed textures and large woody debris arrangements can change seasonally depending on antecedent streamflow conditions.

Some measures can be extremely time and budget consuming. For example, to determine whether the fine component of a gravel bar has changed over time or space requires large sample sizes, often leading to the destruction of the feature.

Most techniques require a compromise between very detailed measurements at an individual site or less detail over larger areas. For instance, Trainor and Church (2003) concluded that survey lengths exceeding 35 W_b are needed to capture the variability of the streambed topography. To cover this length usually requires a reduction in the amount of other data gathered. If the focus is on documenting disturbance patterns, channel surveys must exceed 35 W_b.

Consistent measure among different surveyors can also be a problem. Hogan (2001) provided an example for a small stream in which the same piece of large woody debris was measured annually, but by different surveyors. The same log varied in volume between 20 and 84 m^3 over a 15-year period.

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Spatial Measures – Vegetation Cover

PAT TETI

VEGETATION COVER

In most of British Columbia, industrial forestry is less than a century old and many forested areas have never been logged. Therefore, the landscape reflects a wide variety of vegetation types and ages owing to site potential and the histories of natural disturbance, logging, and reforestation.

The type and amount of vegetation strongly affect the transfer of water and energy between the atmosphere and the terrestrial or aquatic environment. Effects on the water balance include interception loss and the removal of soil water by transpiration. Vegetation also affects ground-level heat budgets by intercepting solar radiation, emitting longwave radiation, and reducing wind speeds. Hydrologists use vegetation cover parameters to help understand and explain these processes, but most forest inventory information is collected for timber inventory and planning purposes.

Forest inventory data are maintained by the B.C. Ministry of Forests and Range. Publicly accessible data (http://geobc.gov.bc.ca/) include polygon-level information on the ages, heights, species, stems per unit area, wood volume, and crown closure of trees. These are collected by a combination of aerial photo interpretation and field measurements according to the well-established field of "forest mensuration" (e.g., Husch et al. 2003). Because these data are available for almost all forest land in British Columbia, hydrologists sometimes use them as indicators of hydrologic processes. Additional data are collected if higher spatial resolution, higher accuracy, or more physically meaningful parameters are needed. The following discussion focusses on several parameters of special interest to forest hydrologists.

Crown Closure

Most forest vegetation cover parameters are based on optically detected presence or absence of tree crowns within a specified viewing angle as viewed from above or below the canopy. The most common example is the percent of ground area occupied by tree crowns. It is physically meaningful and widely used, and is reported in British Columbia's forest inventory database as "crown closure." There is some potential for confusion, however, because of the differing terminology and measurement methods used. Vora (1988), Cook et al. (1995), and Jennings et al. (1999) used "canopy cover" to refer to the percent area occupied by vertical projections of tree crowns. Jennings et al. (1999) used "canopy closure" to mean the percent area occupied by canopy in the entire hemisphere above a point on the ground. In British Columbia's forest inventory, crown closure is estimated by aerial photo interpretation, but its accuracy has not been tested because it is not used for predicting timber supply (L. Bowdidge, B.C. Ministry of Forests and Range, pers. comm., 2007). On an aerial photo, the viewing angle of tree canopies deviates from the vertical by increasing amounts with increasing angles from the photo nadir, thereby increasing the apparent footprint of tree crowns and potentially causing crown closure to be overestimated. In principle, measuring crown closure from below is the same as from above; however, measuring from below offers more options for viewing angles and instruments.

When done at ground level, defining the parameter and sampling it over space are particularly important because of the many potential parameters and their tendency to be highly variable within a stand. Some parameters require long-duration measurements with expensive equipment and are therefore not easily applied over large areas. The emphasis here is on parameters that can be measured quickly at a point on the ground, thereby allowing spatially representative samples to be collected within a stand.

The field of view in which canopy is observed from below is often described in terms of a cone centred on the zenith with a specified radius, or "zenith angle." This corresponds with polar co-ordinates where the angle can be measured either from the zenith or from the horizon (Figure 17.7).

Several simple instruments are designed to allow ocular estimates of percent canopy within different zenith angles. Percent canopy measured from below within a small zenith angle corresponds to the above definition of "crown closure." One of the most commonly used ground-based methods for measuring it is the "moosehorn," which has a zenith angle of approximately 10°. Bonnor (1968) compared average canopy densities measured with a moosehorn in hardwood and softwood stands with cover estimates made using aerial photos and found the two methods to be within 10%. Ganey and Block (1994) described a "vertical sighting tube," which projects a dot at the zenith, thereby allowing presence or absence of canopy to be estimated from below, similar to a line-intercept sampling method.

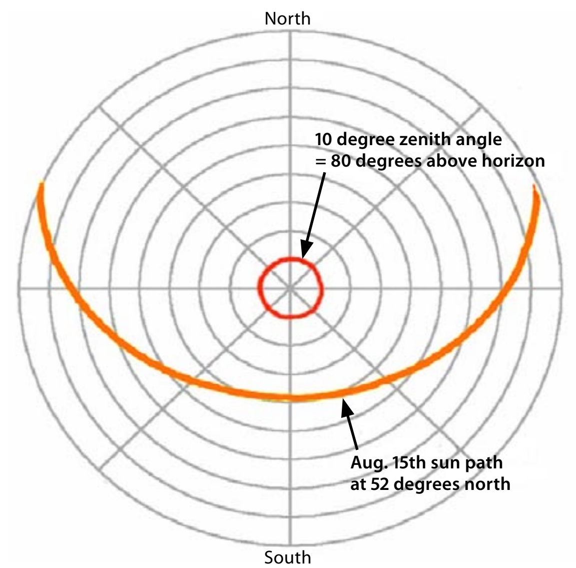

FIGURE 17.7 *Polar co-ordinate representation of a hemispherical field of view centred on the zenith.*

The "spherical densiometer" (Lemmon 1957) is a small instrument with a concave or convex mirror that provides an off-zenith field of view. If used in all four cardinal directions as intended, this densiometer provides a zenith angle of about 50° (Teti 2001). Although the spherical densiometer is simple and convenient, researchers have identified some concerns with its use. Bunnell and Vales (1990) and Cook et al. (1995) noted that measurements by spherical densiometer are consistently higher than crown closure (as defined above) as would be expected due to tree geometry. Teti (2001) noted some issues with the optical quality of the spherical densiometer's mirror. For different zenith angles of different instruments, Bunnell and Vales (1990) noted that researchers should define canopy parameters according to the processes that control the phenomenon they are trying to explain.

Shade and Transmitted Solar Radiation

Various types of radiometers and data loggers are available for measuring radiant energy and can therefore document differences in solar radiation above and below the canopy with precision (Hardy et al. 2004). However, these are sufficiently expensive and cumbersome that it is difficult to use them to collect spatially representative samples under the canopy. For example, Hardy et al. (1997) found that radiation at a single point was inadequate to estimate the average snowmelt energy budget under a forest canopy. Simpler instruments can be used to collect many measurements of index parameters in a relatively short time and make it practical to estimate average shade or radiation over the scale of the forest stand or stream reach.

In forest hydrology, "shade" is usually used in the context of summertime stream temperature studies and refers to the reduction in direct solar radiation at the stream surface by vegetation and other obstructions. The first simple shade parameter suggested for managing summertime stream temperature was "angular canopy density" (ACD) and was defined for a point on the ground or on a stream's surface by Brazier and Brown (1973) as percent shade from 10 a.m. to 2 p.m. It can be estimated with a spherical ACD meter (Teti 2001) or from fisheye photographs. The Solar Pathfinder (Platts et al. 1987) and the Horizontoscope (Brang 1998) allow a user to estimate percent shade from sunrise to sunset. The ACD meter, Horizontoscope, and Solar Pathfinder rely on ocular estimates and are therefore subject to bias and operator variability, both of which can be reduced with training (Teti and Pike 2005).

A more rigorous definition of shade is percent attenuation of incoming direct solar radiation over a full day. This has been referred to as "effective shade" by Allen and Dent (2001) and can be estimated by applying a radiation model to the raw canopy data. The Solar Pathfinder includes tables of incident radiation at different times of day, thereby allowing the calculation of solar energy exposure or effective shade. Software packages such as Gap Light Analyzer (www.rem.sfu.ca/forestry) allow estimates of solar radiation from fisheye canopy photos using radiation models for any time of the year and for different atmospheric conditions. Indeed, the analysis of hemispherical canopy photos provides a basis for testing the accuracy of shade and radiation parameters measured with simpler instruments (e.g., Chen et al. 1997; Englund et al. 2000; Bellow and Nair

2003; Kelley and Krueger 2005; Fiala et al. 2006). It also allows the objective comparison of the degree of correlation between different parameters. For example, Teti (2006) found that average ACD measured on fisheye photos was a very good predictor of average effective shade calculated from the same fisheye photos on 44 stream reaches ($r^2 = 0.93$).

View Factor

View factor is a useful concept in the transfer of longwave radiation between the ground (or snow) and overhead objects because the sky and foliage are often at very different temperatures, thereby affecting the contributions to radiant flux. Canopy view factor is defined as the integral of canopy density at different zenith angles weighted by the cosine of the zenith angle. Assuming that the hemisphere above a flat surface consists of only canopy and sky, canopy view factor + sky view factor = 1. Because of its dependence on the distribution of canopy within the whole hemisphere, it is best determined by analyzing hemispherical canopy photos (e.g., Thyer et al. 2004).

Leaf Area per Unit of Ground Area

The surface area of leaves and needles per unit of ground is an important forest parameter because it is related to the ability of the canopy to store intercepted precipitation and transpire water during the growing season. Leaf area index (LAI) is defined as:

$$\text{LAI} = A_f / A_g \qquad (17)$$

where: A_f is one-half the total surface area of foliage over a given unit of ground (Chen and Black 1992), which for deciduous leaves equals the surface area of one side, and A_g is the ground area.

Direct measurement of forest A_f is a labour-intensive task, so considerable work has been done to estimate it by indirect methods from below and above the canopy. Chen et al. (1997) and Frazer et al. (1997) discussed the use of hemispherical photography, the Licor LAI-2000, and the Sunfleck Ceptometer for estimating LAI from ground level and Turner et al. (1999) discussed its estimation from satellite imagery.

Canopy Photography

Canopy photography can be used to estimate any of the parameters described above. It is slower in the field than many of the previously described methods, and photo analysis requires time, but it provides a permanent and versatile record of the canopy. Depending on the purpose, a fisheye lens is not necessarily required. If a 180° field of view is not needed, a lens with a narrower field of view will provide higher resolution and image quality; however, hemispherical canopy photography is most common for research because it is the most versatile. In any case, the lens geometry must be known and camera orientation must be controlled in the field so that image pixels correspond with known locations in the celestial hemisphere during analysis. With a camera and lens mounted on a tripod with a bull's-eye level, the location of the zenith on the image can be determined by positioning the lens directly under a reference mark with a plumb bob and taking a photo. Repeatability of levelling can be determined empirically. Automatic gimballed levelling camera mounts are available but add considerable bulk. Horizontal orientation can be controlled by including a compass-bearing reference in each photo. Electronic compasses with LEDs indicating direction are available for fisheye lenses or a visible target can be held in the field of view indicating a direction from the lens. Knowing the location of the zenith and a cardinal direction allows a photograph to be oriented for analysis. Lens geometry may be provided by the vendor or determined by photographing a geometrically known or marked-up space (e.g., Clark and Follin 1988). Note that the wider a lens's field of view, the more the resulting image deviates from an equal-area projection (Herbert 1987).

Digital cameras and lenses tend to be smaller and lighter than their 35-mm film counterparts, thereby facilitating use in the field. Film cameras offer the highest-quality hemispherical imagery but require the digitization of each image before analysis. Differences in results between these two acquisition methods have been found (Englund et al. 2000; Frazer et al. 2001), but these are not large enough to undermine the value and convenience of digital cameras for most purposes.

The ability to discriminate sky from canopy within an image is fundamental to all canopy photo analyses. This is usually referred to as "binarization" or "segmentation" and was traditionally based on a single threshold value for every image pixel, thus requiring a uniform overcast sky for accurate results. Edge detection algorithms work by determining local differences in brightness rather than absolute values (Nobis and Hunziker 2004). Sidelook, a public domain software package that implements this algorithm for discriminating vegetation from sky, is available at www.appleco.ch. When working with colour images, Sidelook performs its operation in any of the three colour channels. The blue colour channel generally provides the best discrimination between sky and canopy (Frazer et al. 2001; Nobis and Hunziker 2004; Teti and Pike 2005).

Several commercial and public domain software packages are available for extracting different canopy parameters and for estimating the amount of direct and diffuse solar radiation on different days of the year based on models of sun paths and atmospheric conditions. Many of these are described by Roxburgh and Kelley (1995), Frazer et al. (1997), and Bellow and Nair (2003). Hardy et al. (2004) found that solar radiation calculated with Gap Light Analyzer (mentioned previously) was a good substitute for global radiation measured with pyranometers under a forest canopy.

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Spatial Measures – Remote Sensing

NICHOLAS C. COOPS

REMOTE SENSING

This subsection provides readers with some practical guidelines to consider when seeking to use remote sensing imagery in hydrological applications, as well as a short overview of current applications and uses of remote sensing technology.

Since the invention of photography, it was apparent that an aerial perspective provided important information on the spatial patterns on the Earth's surface and therefore aerial imagery quickly became a critical tool for resource managers. When considering the use of remotely sensed data for hydrological applications, spatial and temporal scale need to be examined in association with the observed hydrological patterns and processes. The characteristics of remotely sensed data (be it digital or photographic) are often referred to as the image resolutions and relate to four basic properties: (1) spatial, (2) spectral, (3) temporal, and (4) radiometric resolutions.

The spatial resolution indicates the size of the minimum area that can be resolved by a detector at an instant in time (Strahler et al. 1986; Woodcock and Strahler 1987). In the case of digital sensors, an instrument that has a spatial resolution of 30 m is typically able to resolve any 30 × 30 m area on the landscape as one single reflectance response. When selecting a data source for hydrological applications, spatial resolution will be a critical factor and generally imagery with a spatial resolution near the size of the objects of interest is usually preferred (Lefsky and Cohen 2003). Table 17.11 and Figure 17.8 outline the optimal applications associated with different spatial resolutions. Generally, broad-scale phenomena are best characterized by low spatial resolution imagery (e.g., for monitoring vegetation phenology across Canada). Conversely, high spatial resolution data are more appropriate for applications that re-

FIGURE 17.8 *Illustration of spatial resolution and subsequent information content of three common image spatial resolutions: 30 × 30 m, 10 × 10 m, and 2.5 × 2.5 m. The underlying image is a digital photograph. Image provided courtesy of J. Heath, Terrasaurus Ltd., Vancouver, B.C. Figure adapted from Wulder et al. (2006).*

TABLE 17.11 *Relationship between scale and spatial resolution in satellite-based land cover mapping programs (adapted from Franklin and Wulder 2002)*

Spatial resolution	Nature of suitable forest disturbance targets
Low	Small-scale disturbances (100–>1000 m); detectable with sensors such as NOAA AVHRR, TERRA/AQUA MODIS, SPOT VEGETATION
Medium	Moderate-scale disturbances (10–>100 m); detectable with sensors such as Landsat Thematic Mapper™, SPOT, RADARSAT I and II, and Shuttle platforms
High	Large-scale disturbances (0.1–10 m); detectable with aerial remote sensing platforms (e.g., photography), IKONOS, QuickBird, Worldview

quire a greater level of spatial detail, such as watershed-level leaf area index.

In addition, the spatial extent of each image data set and the revisit capacity of the satellite system need to be considered in conjunction with data costs. Low spatial resolution imagery typically covers larger spatial extents and is less expensive than high- or medium-resolution data; however, trade-offs exist related to spectral and spatial resolution for increased spatial coverage. Likewise, lower spatial resolution sensors have the advantage of finer temporal resolution, as low-resolution satellite images have revisit times of days rather than weeks. Conversely, high spatial resolution data sets generally have smaller spatial extents, higher cost, and longer nadir revisit times (Coops et al. 2006).

The temporal resolution is the time required for a sensor to return to the same location on the Earth's surface. This revisit time is a function of the satellite orbit, image footprint, and the view angle of the sensor (off-nadir imaging). The timing of image acquisition should be linked to the target of interest. Some environmental processes may have specific time intervals (e.g., snowfall, leaf defoliation) when imagery must be collected to capture the required information (Wulder et al. 2006), whereas other disturbances may be less time specific, such as harvesting operations or land cover change, allowing increased flexibility in data acquisition.

The digital sensor or camera is sensitive to a wide range of wavelengths in the electromagnetic spectrum. The spectral resolution of a sensor indicates the number and the width of the spectral wavelengths captured by a particular sensor. By changing the number or spectral width of the sensor, characteristic reflectance properties of the surface can be accurately portrayed. Sensors with more bands are described as having an increased spectral resolution (Lefsky and Cohen 2003). Currently, most operational satellite-based remote sensing systems have a small number of broad spectral channels (< 10). However, an increasing number of airborne and space-borne instruments can produce hyperspectral data (e.g., instruments with > 200 narrow spectral bands); as a result, these data are becoming more widely available.

Finally, the radiometric resolution indicates the actual information content of an image and is often interpreted as the number of intensity levels that a sensor can use to record a given signal (Lillesand et al. 2004). Increased radiometric resolution increases the capacity of a sensor to detect finer changes in reflectance. In addition to considering the resolution(s) of the required imagery, sensors can also be categorized as either active or passive. Passive, or optical, remotely sensed data are collected by sensors sensitive to radiation from 400–2500 nm as well as surface temperature (emittance at 10.4–12.5 μm). Aerial photography and imagery from the Landsat, SPOT, IKONOS, and QuickBird satellites, for example, are all passive sensors and are the most commonly applied in vegetation and forestry applications. Active remote sensing systems emit energy and then measure the return energy that is reflected back to the instrument. These active sensors can therefore operate under a wide range of conditions not limited by the Sun's illumination (Lefsky and Cohen 2003). Radar and lidar systems are both examples of active sensors. In the case of radar, microwaves with 1 mm – 1 m wavelengths are applied, whereas lidar typically uses pulses of near-infrared radiation.

The choice of active versus passive systems for forest hydrological applications depends on the information required. In the case of radar, the longer wavelengths interact with forest canopy structure, with the signal backscatter correlated to the size of elements in the forest stand. Radar data are available on both airborne and space-borne platforms. Lidar systems emit pulses of infrared radiation and measure the time it takes for pulses to reach, and then be reflected from, the surface (Lefsky and Cohen 2003). Lidar data are typically collected as single points; therefore, the land surface is sampled rather than imaged, and so full coverage is not achieved. Most commonly found on airborne systems, lidar surveys typically have sampling densities of 1–5 m depending on the system, altitude, and speed (Lim et al. 2003). These points are then processed to extract the ground surface and canopy information. Lidar data can also provide detailed information on the vegetation canopy, as laser pulses also intersect with vegetation. As a result, very accurate information on tree height, and structural characteristics such as vegetation cover at different heights, can be predicted using this technology (Lim et al. 2003).

A detailed listing of remote sensing data sources is available at several Internet sites including the Canadian Centre for Remote Sensing (www.ccrs.nrcan.gc.ca). Standards and guidelines for the use of remotely sensed data for vegetation resources inventory purposes in British Columbia are available from the B.C. Ministry of Forests and Range (www.for.gov.bc.ca/hts/vri/standards/index.html).

Hydrological Applications of Remote Sensing Data

Over the past two decades, remote sensing technology has played an increasing role in hydrological applications. Several techniques that apply remote sensing technology have become operational, including estimation of snowmelt runoff and classification of land use. Other approaches are still the focus of ongoing research, including flood management, microwave forecasting of rainfall, and estimation of soil moisture profiles (Schultz and Engmann 2000). In addition to directly predicting hydrological processes, remotely sensed data can also play a secondary role by providing information on vegetation cover to help estimate vegetation water use such as transpiration. Areas of hydrology where remote sensing technology is either routinely applied or under development include prediction of precipitation, snow and ice, soil moisture, land cover, and terrain modelling (Schultz and Engmann 2000).

Since the 1970s, significant progress has been made extracting precipitation rates from remotely sensed data; as a result, many state-of-the-art methods for estimating rainfall use remote sensing observations. In general, the approaches detect rain/no rain boundaries and subsequently estimate the rainfall rates to provide an overall estimate of total accumulated rainfall at a location. Near-infrared temperature thresholds are often used with ground-based observations and meteorological models. Other, more detailed techniques use the visible and near-infrared wavelengths as well as passive microwave systems that incorporate information on cloud tops and reflectivity (Barrett 2000).

Snow and ice cover have been successfully estimated using medium to high spatial resolution optical satellite imagery in cloud-free areas, and algorithms have been developed to estimate a range of snow properties including snow area, extent, and snow surface characteristics. The NASA Moderate Resolution Imaging Spectroradiometer (MODIS) and the older Advanced Very High Resolution Radiometer (AVHRR) instruments use comparisons of two or more spectral bands in the visible, shortwave infrared, and thermal channels (Lucas and Harrison 1990) to estimate snow cover with the current generation of MODIS outputs, including 8-day snow products at between 500-km and 1-km spatial resolution. (Data are available at http://modis.gsfc.nasa.gov/data/.) Under cloudy conditions, techniques rely on passive microwaves that can successfully penetrate cloud cover. Passive microwave techniques look at frequency differences of two microwave channels (22–85 GHz or 19–37 GHz) (Fernandes and Rubinstein 2000).

Soil moisture is a critical variable in hydrology, and remote sensing data may assist predicting and extending moisture measurements over larger spatial areas. Microwave remote sensing has, to date, been used to predict surface soil moisture with varying degrees of success. Field-based point measurements are generally more accurate than satellite-based systems; however, subsequent averaging of these point measures over large areas can lead to significant errors (Geng et al. 1996). Using active microwave sensors, short-wavelength radar (such as C band) can be highly sensitive to soil moisture, surface roughness, and vegetation moisture. The most successful results for predicting soil moisture from radar remote sensing therefore occur for applications in which several of these sensitivities are reduced, such as on bare ground and over flat areas. As vegetation cover increases, the capacity to assess soil moisture with remote sensing technology decreases significantly. Techniques using radar tend to incorporate multiple images where key parameters such as surface roughness can be determined using ground-based observations. Then, using a combination of modelling and imagery, soil moisture can be estimated over a period of time. The Canadian satellites RADARSAT I and II have C-band radar instruments that have successfully estimated soil water over bare ground, but results are limited in forested situations (Galarneau et al. 2000).

Information on land cover can also be critically important for hydrological modelling. Numerous studies have confirmed that land cover (e.g., forests and agriculture) and water bodies can all be accurately classified from remotely sensed imagery. Classification techniques include standard methods, such as supervised and unsupervised classifications, as well as the more recent the use of decision trees and neural networks. These land cover classifications are then often coupled with other models and data that allow the estimation of water use based on land cover and land cover change (Rango and Shalaby 1998; Kliparchuk and Collins 2003).

Finally, remotely sensed imagery and aerial photography remain critical data sources for information on the terrain surface. These layers can be critical for hydrological modelling (Ritchie 1996). Photogrammetry remains the most commonly applied approach to measure height information; however, lidar ground return data have recently been gridded into raster coverage using various surface-fitting routines that allow the derivation of slope and aspect information.

Future Perspectives in Remote Sensing

Advances in computer power are ensuring that models are increasingly able to incorporate more complexity in hydrology than previously was the case. Although this may not guarantee more accurate model results, it does allow the application of ongoing modelling over larger areas and at finer spatial resolution. Furthermore, it is expected that advances in computer graphics and simulation will allow the computation and visualization of highly dynamic hydrological processes in time and space (Schultz and Engmann 2000). Given that remote sensing technology is often unable to directly measure key hydrological parameters, future research is likely to focus on the efficient integration of remotely sensed data and theoretical models. Becker (2006) provided the example of the prediction of evapotranspiration, which is currently measured through a combination of surface radiation in the visible, thermal, and radar backscatter combined with information on historical trends through data assimilation. In addition, progress in using remote sensing data in hydrological applications is often constrained by a lack of field observations with which to start up and provide limiting conditions for models, as well as by the necessity to verify and validate the remote sensing predictions themselves (Lanza et al. 1997). As the next generation of satellite and airborne remote sensing technologies becomes available, it is anticipated that advances such as improved radar sensors, enhanced spectral resolution, and the increased use of lidar-based technology will help solve these current difficulties.

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Stream, Riparian, and Watershed Restoration

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HISTORY OF WATERSHED RESTORATION IN BRITISH COLUMBIA

Introduction

British Columbia's forests provide a wealth of economic, social, and environmental benefits. Over the last century, however, as the extent of forest development has expanded, so too have forestry-related disturbances that require restoration. Ecological restoration[1] is the process of assisting in the recovery of ecosystems that have been damaged, degraded, or destroyed (Society for Ecological Restoration International 2004). Initially, the principal focus of restoration in British Columbia was on fish and fish habitat. More recently, concerns have broadened to encompass a wider range of ecological and social values (e.g., threatened or rare species, climate change mitigation).

This chapter provides a review of the various watershed, riparian, and stream restoration approaches that have been applied over the last 20 years in British Columbia. Although previous habitat restoration and compensation programs for mining, highways, and hydroelectric projects also contribute to this body of knowledge, the focus here is on methods applied in British Columbia to address forest disturbances. This chapter provides a history of watershed restoration in British Columbia, outlines watershed restoration planning principles, and then specifically discusses various hillslope, road, riparian, floodplain, and stream channel restoration approaches that have been applied in the province. The chapter concludes with a discussion of several emerging watershed restoration topics.

Note that content for this chapter was drawn from many key references, as well as the personal experiences of the authors and their colleagues. Furthermore, some of the generalizations in this chapter may not be applicable to all areas of the province. As with every developing science, several schools of thought have emerged on restoration, and thus the methods covered in this chapter may not be universally accepted by all practitioners. Readers are encouraged to review the many supporting documents cited in this chapter and to review the specific watershed qualities and issues discussed to determine whether the information presented applies to their particular watershed restoration issues.

Historic Forest Development Disturbances

Forest practices have evolved dramatically over the last 40 years. Poor logging practices in the past left a legacy of watershed disturbances that have been

1 In this chapter, restoration means returning a site to a target condition. The target condition may not be the same as the pre-disturbance condition, but it is usually based on a desired level of function. Rehabilitation refers to the activities carried out to meet that primary goal.

the focus of many restoration efforts in the province. Some of the more significant historic disturbances included (1) logging of floodplains, fans, and riparian forests; (2) cross-stream yarding and removal of wood from within stream channels; (3) harvesting terrain features that were susceptible to instability or erosion, such as gullied slopes, escarpments, and steep, unstable, or marginally stable slopes; and (4) poor road construction practices.

Logging of floodplains, fans, and riparian forests
In many areas, the logging of floodplains, active fans, and riparian forests along alluvial streams led to increased channel bank erosion and subsequent channel destabilization, widening, and sediment aggradation (Figure 18.1; Wilford et al. 2005). In many cases, logging of riparian forests also resulted in a loss of large wood debris (LWD) recruitment. In addition to these physical channel effects, the removal of riparian vegetation resulted in short-term losses of shade, cover, and food sources.

Cross-stream yarding and wood removal
In some channel types, the loss of LWD through cross-stream yarding disturbance or direct removal resulted in long-term loss of channel structure (i.e., pools, habitat features) and increased sediment transport, which can cause a coarsening of channel bed material (Figures 18.2 and 18.3).

Harvesting unstable or marginally stable terrain
Landslides occur naturally in many British Columbia

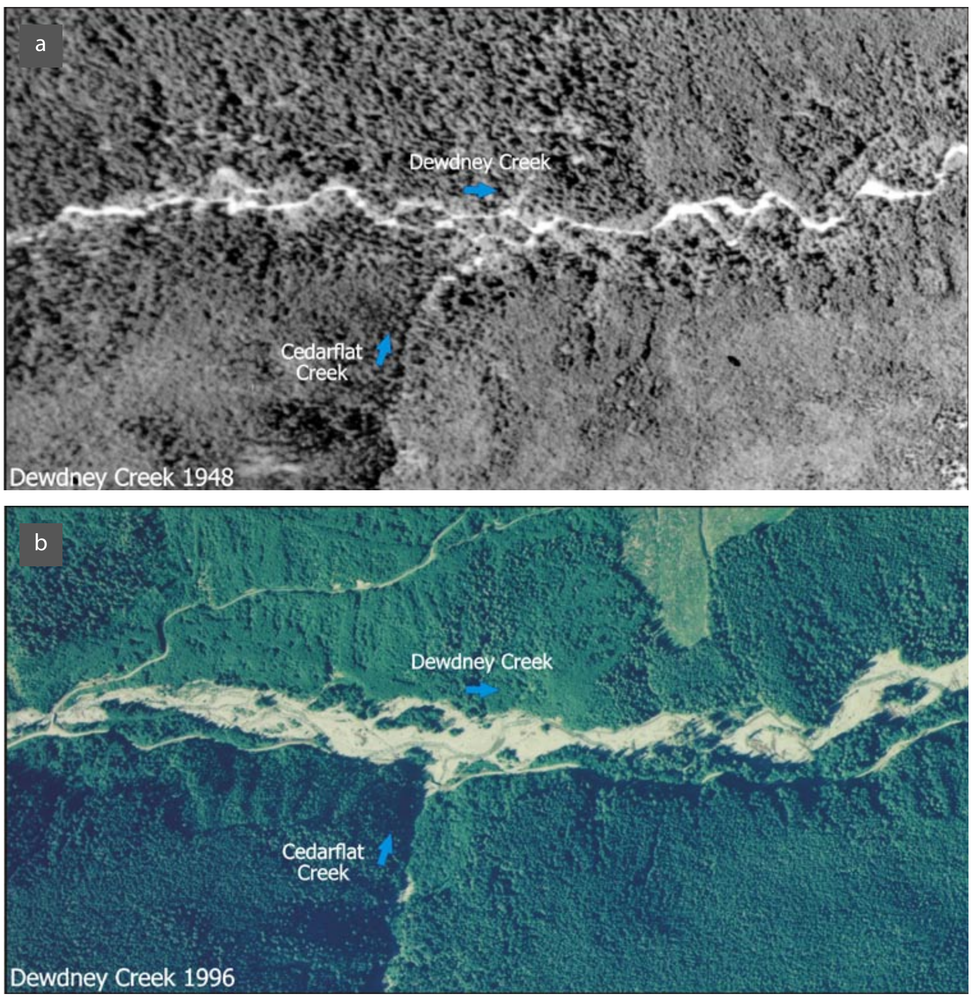

FIGURE 18.1 *Historical air photos showing the changes (increased channel width and increased sediment loading) associated with forest harvesting along Dewdney Creek, a tributary to the Coquihalla River near Hope in (a) 1948 and (b) 1996. (Image compilation: M. Miles)*

FIGURE 18.2 *In alluvial streams in natural coniferous forests, large woody debris stores sediment, creates pools and channel structure, and provides habitat elements. Tributary in an unlogged area of Doc Creek watershed, mainland coast. (Photo: G. Horel)*

FIGURE 18.3 *Where large woody debris has been lost or removed from alluvial streams, channel structure is lost, the channel bed becomes uniform (planar), and the bed material coarsens. Stream in second-growth forest on central Vancouver Island. (Photo: G. Horel)*

landscapes and are important sources of coarse sediment for stream substrates and spawning gravels. In some regions, however, sediment supply significantly increased because of logging on erodible or unstable terrain (Figure 18.4). Increases in sediment supply can result in higher rates of sediment loading, which causes pools to infill and channel changes in alluvial streams, including aggradation, changes in bed material texture, widening, and dewatering at low flows, which affects habitat conditions.

Road construction

Historically, road construction practices often did not consider the stability of road cuts and fills on steep slopes. Road cuts and ditches altered drainage and made no provision for fish passage or sediment and erosion control around stream crossing structures. Key problems associated with poor road construction practices include:

- oversteepened, unstable fills on steep terrain;
- high, unstable cutslopes;
- surface flow and groundwater interception by road ditches and diversion/concentration onto slopes below the road;
- inadequate cross-drain culvert design; and
- use of stream crossing structures that impeded fish passage, restricted streamflow, and (or) had unstable approach cuts and eroding fills.

As a result of these issues, landslides and erosion from and below old roads has been a major source of increased sediment to streams (Figures 18.5 and 18.6).

Evolution of British Columbia Forest Practices and Watershed Restoration

The recognition that poor forestry practices were having negative impacts led to the development and implementation of restoration strategies for degraded sites (Carr 1985). Early restoration efforts in British Columbia sought to control damage, and consisted largely of hydro-seeding and silvicultural plantings of cut and fillslopes and landslide scars. Nevertheless, it soon became apparent that many of the watershed problems could not be adequately addressed by hydro-seeding and seedling planting alone (Homoky 1987). In 1987, the *British Columbia Coastal Fisheries/Forestry Guidelines* were introduced (with full implementation in 1988) with the intention of improving harvesting practices around streams (B.C. Ministry of Forests et al. 1988). In conjunction with these guidelines, incentives were provided through the stumpage system to do remedial work on roads (e.g., Action Assessment Plans). This was the first broad initiative in British Columbia to

FIGURE 18.4 *Examples of landslides related to forestry development in two harvested areas on the west side of Vancouver Island. (Photos: T. Millard)*

FIGURE 18.5 *Misery Creek in the mid-Coast Mountains of British Columbia illustrates landslide and erosion problems that can occur from road construction on steep, unstable terrain. (Photo: M. Miles)*

manage road-related erosion and instability through deactivation. Also in 1988, forest companies became responsible for reforestation, and a strong effort to plant backlog areas helped reduce erosion and accelerate the hydrological recovery of logged sites (W. Warttig, Interfor, pers. comm., Nov. 2007).

In the early 1990s, public concern over forest practices heightened as it became evident that landslide frequency had increased as a result of accelerated harvesting on steep terrain coupled with poor road-building techniques (Chatwin et al. 1994). The *Forest Practices Code Act of British Columbia*, enacted in July 1995 and implemented in 1996 after a transition period, dramatically changed forest practices to reduce the need for restoration. Key changes affecting watershed condition included:

- establishment of specified riparian management zones and reserves;
- avoiding destabilization of fans on the coast;
- identification of unstable or potentially unstable terrain for both roads and cutblocks, and avoidance of harvesting or road construction that would lead to a high hazard of landslides;
- higher standards for road construction, maintenance, and deactivation; drainage design; and culverts, including the introduction of full-bench and end-haul construction as standard practice for roads on steep slopes (B.C. Ministry of Forests 2002); and
- specific guidelines for stream crossings and fish passage to minimize sediment introduction to streams, to protect against erosion at the crossing site, to prevent encroachment into the stream channel, to provide sediment and large woody debris transport through structures, and to ensure that fish passage[2] was not impeded (B.C. Ministry of Forests 2002).

Recognizing that a formal program was needed to improve the condition of disturbed watersheds, the British Columbia Ministry of Forests initiated the Watershed Restoration Program (WRP) in the fall of 1993. In 1994, Forest Renewal BC (FRBC) was established with funding from the stumpage system. The purpose of FRBC was to provide a funding mechanism not only for watershed restoration activities, which were expanded to include the Terrestrial Ecosystem Restoration Program (TERP), but also for a wide range of other activities related to forest management, including research. Watershed restoration projects under these programs have mostly been led by forest licensees, or had a forest licensee as a major partner. An important role of the WRP and FRBC and its successor programs has been to develop standards and guidelines for assessments and restoration activities.

2 The free computer program, FishXing3 (www.stream.fs.fed.us/fishxing/index.html), was developed to assist engineers, hydrologists, and fish biologists in evaluating and designing culverts for fish passage.

FIGURE 18.6 *Example of road fill landslide, West Coast Vancouver Island. (Photo: T. Millard)*

WATERSHED RESTORATION PLANNING

Restoration Goals

For many forms of watershed development, such as mines, highways, railways, hydro-infrastructure, agriculture, and urban development, restoration measures are often compensatory since facilities and infrastructure are frequently established for the long term. Forest development, however, differs in that only a small portion of fixtures are permanent (e.g., major mainlines, log sorts); most are short term (e.g., branch and spur roads, landings, temporary camp sites). Additionally, considerable opportunity exists to minimize disturbances in future forest development. For example, helicopter yarding can be used to avoid road construction in harvesting and access areas where winter roads or temporary roads on potentially unstable terrain would have traditionally been used. These opportunities are typically not available to other kinds of development at fixed locations, such as transportation or utility corridors.

Significant disturbance caused by infrastructure developments can be substantially mitigated, or the infrastructure can be decommissioned altogether. Even with permanent infrastructure, opportunities exist to mitigate problem sites (e.g., relocating sections of mainline). In forested settings, it is not unrealistic to plan for recovery to pre-disturbance conditions for processes that may take decades. It is also feasible to consider restoration approaches that employ short-term measures with the objective of having nature take over. In other kinds of development, particularly in urban areas, this may not be possible if natural processes have been permanently altered. Hence, the type of watershed development that occurs will have a strong influence on restoration goals and planning.

Restoration goals provide the purpose of restoration—that is, the end points that restoration efforts are to achieve and the basis for project evaluation. For example, an overarching restoration goal may be to re-establish ecological processes and functions by means of the following objectives:

- promoting a recovery trend toward pre-disturbance conditions,
- mitigating impacts where restoration is not feasible, and
- improving or developing habitat to compensate for habitat permanently lost or irreversibly degraded.

Rehabilitation treatments should not be confused with restoration goals (Atkins et al. 2001). Rehabilitation measures, such as road deactivation or the construction of off-channel habitat, are employed to help reach restoration goals but are not goals in themselves.

Restoration Prioritization and Planning

A watershed or sub-unit may be selected for restoration because of specific interests in the watershed and concerns over known impacts. Landscape-level assessments can also be done to select watershed units for restoration based on criteria for watershed disturbance and relative fish values. A number of approaches for prioritizing watersheds for restoration have been developed by government agencies, forest licensees, and watershed specialists. One example is illustrated in Figure 18.7.[3] Green (2005) offers another example of watershed risk analysis. Conducting a risk analysis (e.g., Wise et al. 2004) is also strongly recommended as part of restoration planning.

Once restoration areas are prioritized, it is important to set specific restoration goals and project objectives. The next step is to characterize the hydrologic and geomorphic processes in the watershed and identify sensitive areas, disturbances that have occurred, and current watershed trends. Selection of sites for treatment and rehabilitation measures to be employed should consider the following factors.

- the severity of the existing disturbance at the site
- the present trend—for example, is the condition stable, worsening, or improving?
- in the case of roads on steep slopes, the potential for further landslides to occur, and the downslope consequences thereof
- geomorphic and hydrologic risk factors associated with treatment and the likelihood of success of remedial measures; for example, on landslide headscarps or on unstable fans or alluvial streams
- for vegetation treatments, silvicultural risk factors associated with treatment, and the likelihood of success
- subsequent maintenance requirements to ensure that the proposed measures will continue to be effective for their intended design life
- potential risks to the proposed measures from natural or development-related events such as landslides, windthrow, erosion, or flooding
- the cost of the proposed measures and the expected benefits
- the extent to which the site and the proposed treatments contribute to achieving the restoration goals
- with respect to priorities and scheduling, the ranking of each site and the proposed measures compared to other sites/measures

Plans can then be developed to systematically address the following types of restoration (as applicable) in a particular watershed (Figure 18.8):

- hillslope and road restoration
- riparian and floodplain restoration
- stream channel restoration, including erosion control, and in-stream habitat, fish passage, and off-channel restoration

When implementing restoration activities, it is generally preferred to address upslope and headwater conditions first and then work progressively downslope and downstream. This is important where hillslopes and roads are directly coupled to streams so that riparian and stream treatments are not jeopardized by further landslides or sediment transport from these upslope sources (Hartman 2004). Johnston and Moore (1995) proposed that it made little sense to invest in lower sections of a valley or river if landslides or fluvially transported sediment continue to adversely affect restoration efforts. Nevertheless,

3 Horel, G. 2007. Tree Farm Licence 37 watershed indicators. FIA Investment Schedule COTFL376654, Project No. 6654004. B.C. Min. For., Forest Investment Account (FIA), Land Based Investment Invest. Program. Unpubl. report.
Horel, G. 2008. Tree Farm Licence 19 watershed indicators. FIA Investment Schedule COTFL196649, Project No. 6649012. B.C. Min. For., Forest Investment Account (FIA), Land Based Investment Program. Unpubl. report.

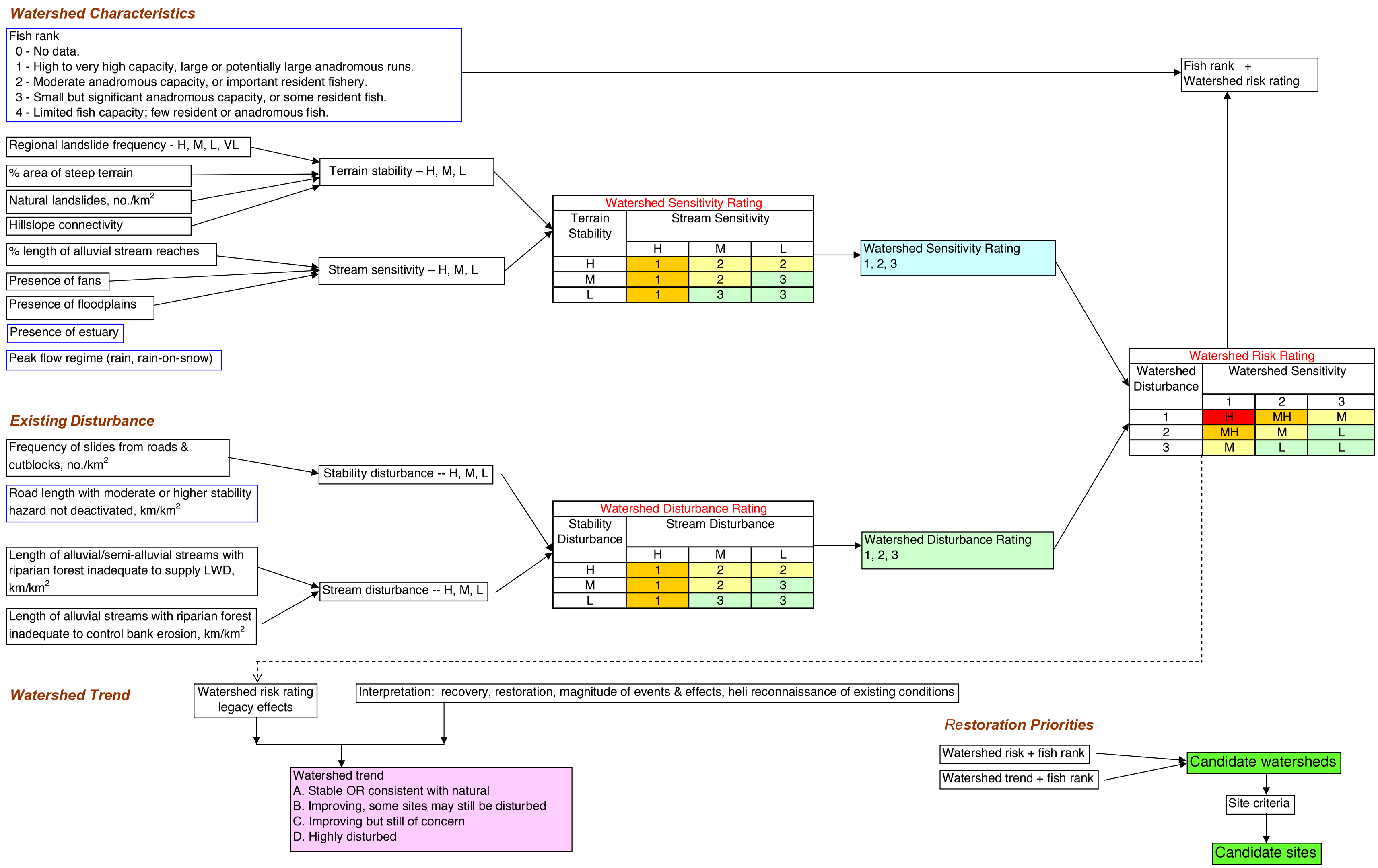

FIGURE 18.7 *Overview risk rating and trend for prioritizing watersheds (Used with permission. Western Forest Products Inc. watershed indicators projects 2006–2008[4]).*

4 Horel, G. 2008. Tree Farm Licence 19 watershed indicators. FIA Investment Schedule COTFL196649, Project No. 6649012. B.C. Min. For., Forest Investment Account (FIA), Land Based Investment Program. Unpubl. report.

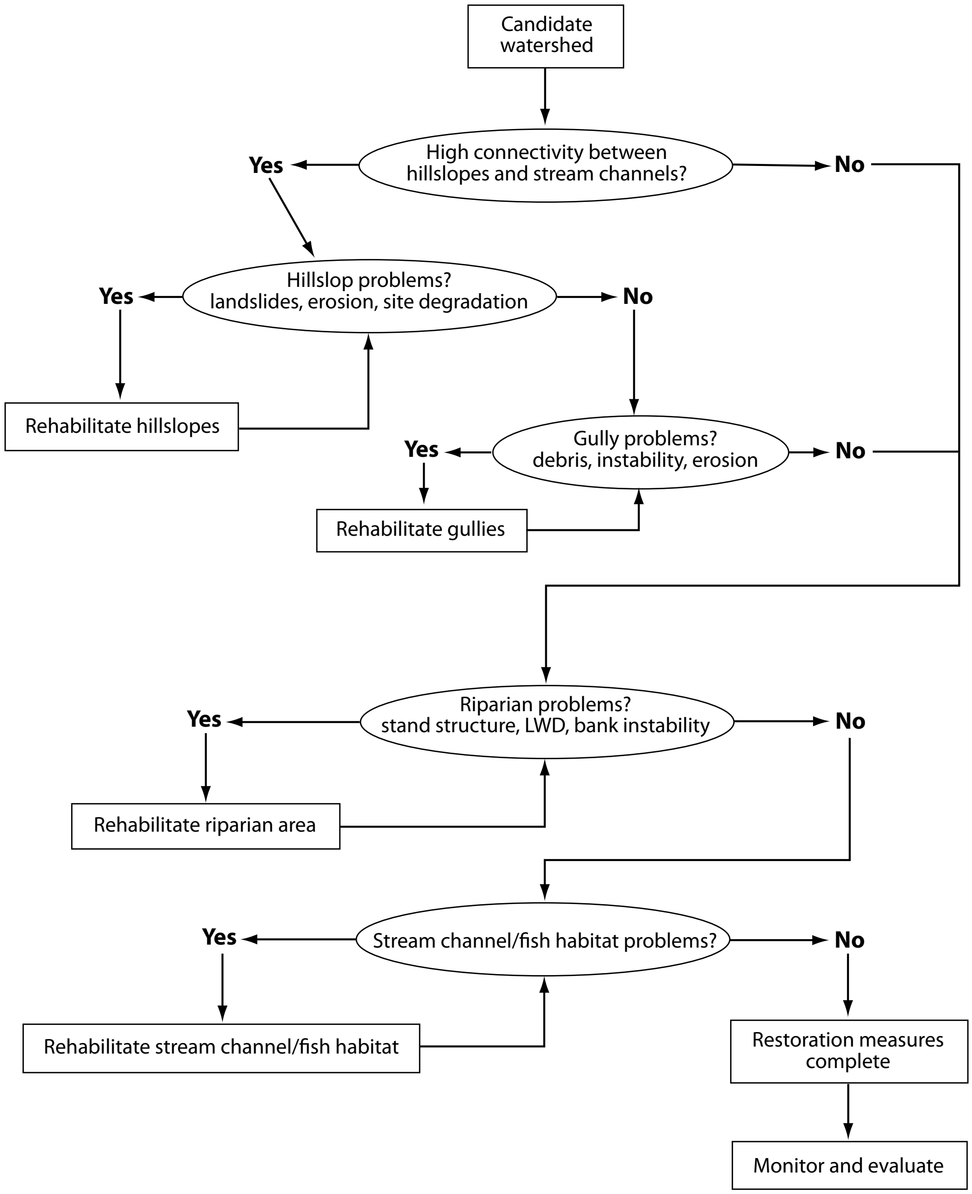

FIGURE 18.8 *Overview of watershed restoration implementation sequence (Johnston and Moore 1995).*

a need may exist to improve stream channel conditions or enhance fish habitat in the short term before all identified upslope work can be completed or the beneficial effects of restoration activities (e.g., conifer growth along riparian areas) are realized. Decisions on scheduling rehabilitation measures should consider the urgency of short-term needs in conjunction with the level of hazard to which in-stream measures could be exposed if implemented in advance of the upslope work.

It is also important to integrate restoration planning with other planning processes, especially in multi-use watersheds. Failure to do so can result in rehabilitation measures that compromise, or are compromised by, other activities. For example, when forest development is ongoing or when other requirements for regular access exist, restoration approaches and rehabilitation activities require planning in conjunction with these other land uses. A good example is where roads were permanently deactivated at considerable expense under watershed restoration projects, only to be re-opened a year or two later for forest harvesting. Restoration activities, such as deactivation, planned in conjunction with other forest development can take advantage of opportunities—for example, the salvaging of logs from wood culverts or buried in fills, or the scalping of road ballast for use elsewhere.

Once rehabilitation activities are completed, the site information should be integrated into data sets that are regularly used for forest management and other planning processes. This is necessary to protect the restoration investment in site works. If rehabilitation measures will require maintenance, then planning needs to ensure that future site access is possible.

Rehabilitation Measures and Approaches

The incorporation of science is a key underpinning of all successful watershed restoration programs (Hartman 2004). Rehabilitation measures generally fall into two main categories: (1) process-based—those that facilitate natural recovery processes (Polster 1989; Walker and del Moral 2003; Walker et al. 2007); and (2) structure-based—those that utilize engineered works (see Slaney and Zaldokas [editors] 1997). These measures are discussed further in subsequent sections of this chapter.

Examples of process-based measures (Atkins et al. 2001) include:

- vegetation re-establishment to promote natural succession processes on gravel bars;
- riparian treatments to enhance conifer growth in second-growth stands, to promote conversion from disturbance-generated deciduous stands to conifer stands, or to establish a natural mix of species in single-species managed stands;
- revegetation of denuded slopes and escarpments using bioengineering techniques; and
- bioengineering measures in scoured gullies to create channel roughness, trap sediment, and promote revegetation.

Examples of structure-based measures include:

- armoured catchment basins to contain landslide material or eroded sediment;
- engineered logjams used for erosion control or flow deflection;
- rock armouring or rock groins to control bank erosion; and
- engineered fills or retaining structures to mitigate road instability.

Some practitioners see these two measures as competing philosophies, whereas most others consider them as complementary, particularly at sites where the implementation of both is possible. Well-designed plans for watershed restoration generally use both approaches, as a need often exists to address physical conditions (which may favour structure-based measures) and facilitate ecosystem restoration (which may favour process-based measures). Furthermore, the lines between the two approaches can be blurred because remedial works at an individual site may incorporate elements of both.

Regardless of the approach used, a thorough understanding of the watershed's hydrologic and geomorphic processes and the scale (e.g., landscape, watershed, or site) at which these act is critical to develop effective and achievable restoration goals and rehabilitation measures. Treatments that accommodate rather than attempt to change or control natural watershed processes are more likely to be successful (Kellerhals and Miles 1996).

Numerous rehabilitation treatments have been developed through restoration efforts conducted in British Columbia and elsewhere (see Slaney and Zaldokas [editors] 1997; Atkins et al. 2001). Rehabilitation measures may be intended for short- or long-term reasons, and may have specific objectives that include:

- preventing further disturbance, such as remediating unstable or eroding roads;
- re-establishing structures to mimic natural conditions that were lost through disturbance, such as the placement of LWD in streams where recruitment of natural LWD has been reduced or delayed by loss of sources;
- enhancing or creating habitat, such as constructing habitat in flooded gravel pits connected to streams to offset habitat loss through disturbance; and
- creating conditions that would allow natural processes to approach targeted levels of function, such as riparian treatments promoting the growth of a natural mix of species in the riparian forest.

An example of a measure with a short-term objective is the construction of artificial habitat features as an interim measure until natural recovery processes have re-established. Many long-term restoration objectives entail the re-establishment of natural successional trajectories on disturbed sites. These will differ depending on the site (i.e., restoration treatments in riparian areas will differ from those applied to hillslopes). Permanent deactivation of steep, unstable roads is an example of a measure with both short- and long-term objectives. The greatest benefit is achieved by reduced landslide occurrence in the short term; further benefit is achieved in the long term when the deactivated sites become reforested.

At the planning stage, note that some rehabilitation measures may require ongoing maintenance for the duration of the measure's design life. The long-term success of these measures may hinge on the availability of funding for ongoing maintenance, which is often uncertain. An example is the anchoring of LWD structures in areas of a stream where these features would not occur naturally (e.g., transport zone). Without maintenance, these types of structures are unlikely to persist and will ultimately be lost; however, interim measures such as LWD placement can provide enhanced fish habitat and increased fish densities in degraded sites over the short term (e.g., Cleary 2001; Slaney et al. 2001). An important consideration in choosing these types of measures is whether continued site access will be available for maintenance purposes.

HILLSLOPE AND ROAD RESTORATION

Hillslope and road restoration is an integral part of watershed restoration in British Columbia (Atkins et al. 2001), and must be co-ordinated with other forestry or restoration activities. Hillslope and road restoration is normally used to reduce the sedimentation in streams that results from disturbance-related increases in hillslope instability and erosion (see Chapter 8, "Hillslope Processes" and Chapter 9, "Forest Management Effects on Hillslope Processes"). In some cases, the primary purpose of this work is to protect downslope infrastructure or other high-consequence sites from the effects of these events. Another purpose is to restore natural drainage patterns that have become disrupted, for example, by the diversion of water in road ditches; however, restoration of drainage, in the absence of instability or erosion, is rarely a primary goal. Hillslopes that do not exhibit these other hazards are rarely targeted for rehabilitation measures for drainage alone because of cost–benefit considerations and other higher priorities. For example, if road cuts, ditches, and altered drainage courses have substantially revegetated, reopening these roads to re-establish natural drainage patterns can create more disturbance than the intended remedial measures would offset.

Hillslope features identified for rehabilitation measures can include:

- unvegetated or eroding landslide tracks,
- eroding or scoured gullies,
- excessive wood accumulations (logging slash) or debris jams in gullies,
- unvegetated or eroding escarpments,
- unstable road cuts,
- oversteepened unstable road fills (Figure 18.9), and
- eroding road ditches.

As mentioned previously, access management is a critical factor when developing hillslope restoration plans. Old roads have been a major source of watershed disturbance (Chatwin et al. 1994), but many are vital infrastructure for long-term forest management and often provide access for recreation activities or to remote facilities (e.g., communications towers, weather stations, research and monitoring sites). In most cases, it is paramount to co-ordinate hillslope restoration and access management with forest planners, other restoration efforts, and other forest users. It is often necessary to weigh the benefits of maintaining access against the hazard of further disturbance from landslides. Some considerations include:

- the hazard of an event (landslide or severe erosion), either from the road itself or initiated by drainage off the road, or from events upslope of the road that would render the road unsafe or unusable;
- the downslope consequences of maintaining access;
- the degree to which hazard or risk can be reduced while retaining access;
- other alternatives for access;
- cost comparison of the access alternatives and remedial measures proposed; and

FIGURE 18.9 *An example of landslides caused by logging road development. (Photo: M. Miles)*

- subsequent maintenance requirements for measures employed to retain road access or to protect the road.

Maintaining road access across hillslopes can also have implications for other hillslope restoration plans (e.g., treatments of gullies and landslide tracks). Rehabilitation measures may need to accommodate not only the road prism but also incorporate protection of the road (e.g., from upslope sediment or debris sources). Landslide or gully treatments in proximity to the road should occur concurrently with remedial road treatments. This can involve structure-based elements such as debris catchments or rock buttressing of cutslopes (Figure 18.10), in addition to process-based elements such as revegetation or bioengineering measures (Figure 18.11).

Although maintaining road access may be a complicating factor in hillslope restoration plans, it provides opportunities for treatment options at other hillslope sites (gullies, landslide tracks), which otherwise might not be feasible (e.g., machine removal of debris jams in gullies). In selecting and prioritizing hillslope sites for treatment, the following factors should be considered, especially where site access is limited.

- likelihood of continued disturbance (e.g., ongoing erosion of landslide tracks or escarpments, further sediment-generating events in gullies, release of debris jams)
- downslope consequences of the treatment
- existing state of recovery and trend
- likelihood of success of the treatment
- options and costs for attaining site access
- the extent of new disturbance if access is reopened weighed against the level of hazard reduction expected from the proposed measures

Road Rehabilitation Measures

The type of rehabilitation measures to be used on roads will depend on:

- whether the road is to be retained or permanently deactivated;
- the degree of access to be maintained; and
- the specific terrain, soil, and drainage conditions along the road.

In this context, permanent deactivation means decommissioning of the road with no provision for future access.

FIGURE 18.10 *A retaining basin was constructed to capture materials that will fall from the slope above. (Photo: D. Polster)*

FIGURE 18.11 *Soil bioengineering was used on this landslide to initiate the natural successional processes that will maintain a vegetation cover on this slope. The rock basin shown in Figure 18.10 can be seen on the left in this photo. (Photo: D. Polster)*

Typically, on roads that are to remain accessible for vehicle traffic, remediation of unstable fills involves partial rather than complete fill retrieval, with endhaul of excavated material trucked to a spoil site. If significant endhaul is required and spoil sites are not located close by, then hazard mitigation may be very costly. In some cases, potential instability can be substantially mitigated while still maintaining viable road access (Figure 18.12). This is most often the case where cutslopes are fairly stable. Even partial fill retrieval can result in a narrower road surface. The required road surface width depends on the class of road and volume and type of traffic; minimum drivable road widths may be acceptable for branch or spur roads but not for mainlines.

To achieve sufficient road width after pullback, road widening into the cutslope is possible if the cutslope is sufficiently stable. Other options include using engineered fills and (or) retaining measures for fills and cutslopes; however, these measures can become very costly. Therefore, retaining old roads on steep slopes for future use often involves a trade-off with hazard mitigation. Some level of hazard may be acceptable, but in cases of severe cutslope instability or instability in the road bench, it may not be practical to keep the road safe for use or to mitigate stability hazards by means other than permanent deactivation.

Mainlines

Many mainline roads in British Columbia were built decades ago and are part of the active long-term forest road infrastructure. Mainlines also serve remote communities, public campgrounds, and popular recreation areas or are used regularly by public traffic. Mainlines were often built along lower valley slopes or valley floors. Common problems associated with old mainline roads include:

- sections located along eroding streambanks,
- roads located in areas with unstable fills and cutslopes,
- drainage structures that impede fish passage, and
- sections that cross fans and debris flow channels.

Restoration for mainlines usually requires providing sufficient road width or turnouts and sight distance for two-way traffic, which may include both public vehicles and large industrial vehicles. Public safety and liability can be significant issues on mainlines that are required to accommodate large industrial vehicles and/or the mix of traffic and an-

FIGURE 18.12 *Fillslope instability has been substantially reduced by fill retrieval and endhaul; however, the remaining road surface is narrower. (Photo: D. Ostapowich)*

ticipated vehicle speeds. Certain options, such as armoured fords or extended single-lane sections, may not be acceptable in these cases. In general, remedial measures for mainlines are of a higher standard than for other forest roads, and frequently involve engineered works. Because mainlines are regularly inspected and maintained, it is feasible to consider remedial measures that may require maintenance—for example, sediment catchment basins (VanDine 1996), debris racks in front of drainage structures, and settling basins for ditchline sediment. For works in or adjacent to streams, such as drainage structures or streambank erosion measures, fish passage requirements and timing restrictions (fish windows) may apply.

Mainline realignment can be a viable restoration option if requirements for grade and curvature can be met; however, in many cases alignment is constrained by control points (such as major stream crossings) and grades. The cost of realignment may also be prohibitive. Consequently, remedial measures on mainlines often involve accepting either some level of hazard or maintenance requirements at problem sites.

Armoured fords are occasionally used as an alternative to pipe culverts or bridges at sites that experience regular debris flows or avalanches. On mainlines, the factor limiting ford use is usually vertical curvature—the dip required for the drainage way may not accommodate mainline traffic safely. Other alternatives on mainlines, such as low-level bridges designed to overtop in severe storms or debris flows, may be preferred (Figure 18.13). Armoured fords normally require inspection and may need periodic maintenance. Therefore, these structures may be practical along actively used mainlines but may not be an option on other forest roads.

For mainlines that receive continuous use, deactivation measures are usually not an option. Mainlines that access remote valleys may be deactivated for periods of time or may have limited traffic other than logging-related vehicles. In more remote locations, options such as single-lane sections and ford crossings can also be viable in areas with reduced vehicular traffic.

Other roads to be retained

For roads that are not regularly maintained and inspected, remedial measures that require maintenance, such as catchment basins or debris racks, have limited success and are likely to fail (Figure 18.14).

When not in active use, these roads are typically deactivated to some degree. Access requirements might be two-wheel drive, four-wheel drive, all-terrain vehicle (ATV), or restricted vehicle access.

FIGURE 18.13 *Low-level bridge on active mainline, designed to be overtopped during major floods or debris flow events. Tyler Creek, south central Vancouver Island. (Photos: G. Horel)*

FIGURE 18.14 *Debris rack upstream of culvert on unmaintained road. Debris rack had completely filled in and was starting to collapse. (Photo: D. Ostapowich)*

Deactivation of these roads usually involves partial fill retrieval, removal of drainage structures, construction of cross-ditches (Figure 18.15), and armouring, especially at the outlets of cross-ditches. Some landslides may occur from the residual fills on these roads (Forest Practices Board 2005).

In some cases, leaving drainage structures in place and backing them up with downgrade cross-ditches (fail safes) is also an option. The steeper the grade, however, the more difficult it is to construct drivable cross-ditches, and at very steep grades (> 15–20%), it becomes impractical to do so. Regular traffic through cross-ditches can make maintenance of the structures problematic, especially if coarse material for armouring is scarce or unavailable. With regular traffic, downgrade berms in fine-textured soils can become rutted. Regular traffic also retards vegetation growth, leaving the cross-ditch susceptible to erosion. Road users may compromise the function of cross-ditches by filling them with wood or stones to facilitate access. Combined with ruts in the downgrade berm, this can cause the cross-ditch to fail. In these cases, other alternatives include leaving drainage structures in place and maintaining the road, constructing alternative drainage structures (such as cattle guards) instead of cross-ditches, or closing the road to vehicle access.

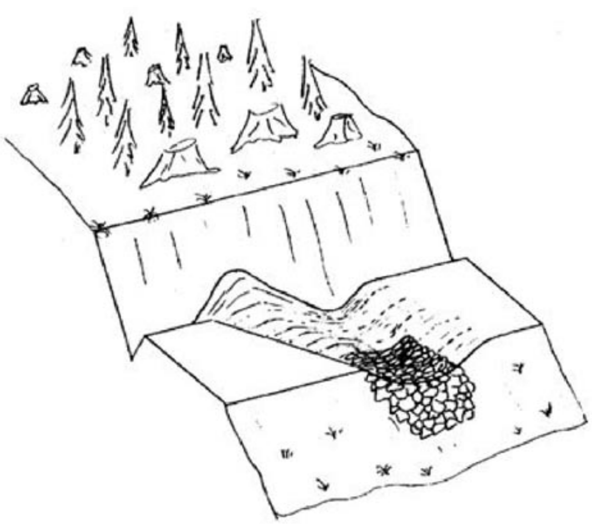

FIGURE 18.15 *Typical cross-ditch (sketch by G. Horel).*

Outsloping is occasionally used as an alternative to constructing cross-ditches, particularly if specific drainage channels have not been disrupted and the intent is to disperse drainage across the road rather than concentrate and discharge it onto areas of potential downslope instability. This technique is limited to fairly flat grades (less than about 8%); at steeper grades, the water tends to run down the road rather than across it. Additionally, outsloped roads may be acceptable for pickup-truck traffic but may be dangerous for large vehicles or for vehicle traffic during periods of snow or ice cover.

Permanent deactivation

Permanent deactivation affords the greatest opportunity to mitigate hazards on unstable roads. The specific deactivation measures chosen will depend on:

- the potential hazard of further landslides or erosion,
- the downslope consequences on specific values,
- the existing state of recovery, and
- the existing access condition.

For substantially overgrown and inaccessible roads, the level of existing hazard should be weighed against the disturbance created by deactivation and the cost of reopening the site. Where stability hazards are not a concern, permanent deactivation measures may be limited to removing drainage structures, restoring channel alignments and gradients, and protecting exposed banks from erosion.

Where a significant hazard of instability exists from road fills or cuts, restoration generally involves completely de-building the road by retrieving all fill and drainage structures, and contouring the site to conform to the adjacent hillslope and channel alignments (Figures 18.16 and 18.17). Excavated fill material is typically placed against the cutslope, although this may not be possible if upslope erosion or landslides have deposited material on the road. Where the road cut is unstable and regressing upslope, it may not be possible to place retrieved fill on top of the cutslope. In this case, any excess fill may require endhauling or transport to a suitable spoil site. Nevertheless, slope drainage and soil strength may be irrevocably changed even with full road removal and complete contouring. Using measures such as scarifying the old road surface to ditch-bottom depth may not restore natural drainage conditions.

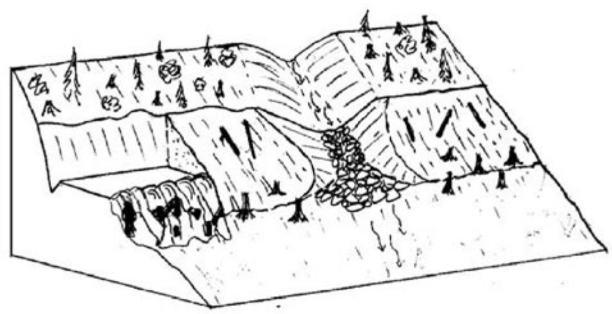

FIGURE 18.16 *Sketch illustrating full fill retrieval and contouring (sketch by G. Horel).*

FIGURE 18.17 *Permanent deactivation and hillslope contouring on a road in south-central Vancouver Island. (Photo: D. Ostapowich)*

With deep fills or long fillslopes, it is often necessary to make two, or in some cases several, passes to retrieve most of the unstable fill. In these situations, using two machines in a double-bench configuration can improve the safety and the efficiency of the work (Figure 18.18).

The extent to which retrieval of all fill can be accomplished depends on the type and size of equipment, operator expertise, and the ability to bench down. The latter can be limited by the presence of bedrock in the bench, instability of the bench itself, and hazardous conditions below the bench, such as a landslide scarp, which makes fill retrieval unsafe.

In practice, fill retrieval can be performed using several excavator types, sizes, and configurations. The choice of machine and configuration will depend on topography, road geometry, soil conditions, footing conditions, other local site factors, and equipment availability as dictated by local construction activity. Although machines with extended booms have been used to reach farther down fillslopes, bucket loads must be smaller so that the machine does not overbalance, thus making the process slower and possibly creating delays in project completion times. An extended-boom machine can, however, allow fill to be safely retrieved when the ability to bench down is limited.

Large excavators (equivalent to the Hitachi 400 series) can be effective on very wide roads with large fill volumes. On narrow roads, effectiveness is limited by the width required to swing the machine. Large, heavy machines require support on stable benches, and thus are usually not suitable when benching down is involved. Machines equivalent in size to the Hitachi 300 series are common in road construction and are generally practical for fill retrieval. A combination of a 200 series and a 300 series machine has yielded good results in deactivating roads with deep fills on steep slopes on south-central Vancouver Island (D. Ostapowich, Ostapowich Engineering Services Ltd., pers. comm., March 2008).

The most important factor affecting the quality of deactivation is the expertise of the operator. Road deactivation on steep slopes is hazardous work that should be done only by highly experienced operators. Inexperienced operators cannot be expected to do the same work safely, which means that either the resulting work will not meet expectations, or worse,

FIGURE 18.18 *Two excavators using a double-bench approach to deactivate a road with deep fills on south-central Vancouver Island. The lower machine passes material to the upper machine, which places it against the cutslope. (Photo: D. Ostapowich)*

that the operator will imperil themselves. Safety plans, including rainfall shutdown thresholds where applicable, should always be in place for deactivation projects.

Despite good equipment and the most diligent work by highly skilled operators, it is often not possible to fully mitigate stability hazards on old roads. Many of these roads were built on naturally unstable or marginally stable terrain. Under today's forest practices, roads would not be built in these types of locations. On these sites, the aim of deactivation should be to mitigate stability and erosion hazards to the extent that it is safely possible. Road deactivation, especially full deconstruction, has dramatically reduced landslide occurrence. Construction standards implemented under the Forest Practices Code significantly reduced the occurrence of landslides associated with new road construction (Horel 2006).

Use of explosives for deactivation

In some situations, deactivation using explosives is a viable option where vehicle access does not exist or would not be practical to re-establish. Explosives have been used for excavating cross-ditches, removing wood and metal pipe culverts, dismantling timber cribs, dislodging wood debris in debris jams, removing sidecast fill, and resloping landslide scarps (Figures 18.19a and 18.19b). Because of the inherent danger associated with the use of explosives, blasting for deactivation measures should be done only under the supervision and control of a highly experienced explosives expert.

Blasting equipment and supplies may be carried in on foot or airlifted by helicopter. Blasting methods have involved various explosive products used in several configurations, including downhole loading, surface loading, and attachment to individual features such as logs, stumps, or culvert pipes. Since access for normal drilling equipment is not usually available, downhole loading is limited to hand-drilling methods.

Generally, the energy required to blast masses of soil or wood is very large and the outcome can be uncertain. Wood and soil tend to blast "dead" (i.e., they absorb much of the explosive energy). As such, downhole configurations are preferred because the blast is confined and more energy is transferred to the soil mass. If difficult hand-drilling conditions preclude downhole loading, then surface blasting may be an option, although the energy is largely un-

FIGURE 18.19 *(a) Unstable fills and steep escarpments along a road section above Kennedy Lake on Vancouver Island. Road access to site was cut off by a large landslide (not visible). (b) Surface blast used to remove fill and trim landslide scarps. Photo shows site after blasting. (Archive photo from MacMillan Bloedel Limited, Kennedy Lake Division)*

confined and enormous explosive power is required to dislodge large soil masses. Thus, surface blasting should be used only where equipment access is not possible and a strong justification exists for the deactivation measures. Typically, an ammonium nitrate and fuel-oil (ANFO) combination is used for surface blasts because of its high gas expansion, whereas dynamite with high "crack" is used for downhole applications.

The use of explosives has its limitations. In removing sidecast fills, for example, it is difficult to control blasting results, and some material may remain after blasting. Blasting can have effects at considerable distances from the site, and can create hazardous sites if unexploded charges remain because of misfires or lack of ignition.

Revegetation of deactivated roads

Numerous forest roads in British Columbia have been successfully reforested after deactivation. Spur roads are often planned as temporary roads that will be reclaimed and reforested soon after logging is complete to reduce site losses (Figures 18.20 and 18.21). Revegetation methods used for deactivated roads will depend on site conditions after deactivation is complete, and on the objectives for revegetation, which may include:

- controlling surface erosion of newly exposed fine-textured soils,
- re-establishing conifer root networks to improve slope stability on steep slopes,
- re-establishing forest stands as part of broader forest management objectives, and
- re-establishing natural vegetation successional pathways.

In deciding whether to plant deactivated roads, forest professionals may consider the following points (Scott Muir, Western Forest Products Inc., pers. comm., June 2008).

- What is the age of the adjacent stands? Will a merchantable crop of trees be established by the time the surrounding stand is available for harvesting (e.g., a time lag of 15–20 years may preclude simultaneous harvesting of the replanted and adjacent stands)?
- Will natural regeneration (e.g., by species such as alder) be sufficient to provide erosion and sediment control?
- Will shading of the road from the adjacent stands impair conifer growth if the road is planted for silvicultural objectives?

FIGURE 18.20 *The culvert was removed at this crossing and the drainage course restored with an armoured swale. Pocket planting was used to establish vegetation in the riprap. (Photo: D. Polster)*

FIGURE 18.21 *This road section is undergoing full deconstruction by retrieving sidecast fill material and placing it against the cut, removing drainage structures, and placing salvaged wood on the regraded slope. (Photo: D. Ostapowich)*

If fill retrieval has not been done and the ballasted road surface remains, the most appropriate revegetation approach depends on the objective. If no reforestation will occur, then revegetation may be limited to seeding cross-ditches for erosion control, with the rest of the site left to regenerate naturally. If reforestation is intended, then the road would usually be scarified to loosen the compacted surface; the ballast would either be removed (ideally for use elsewhere) or mixed with underlying soil material. In some situations, suitable spoil from other sites (e.g., endhaul road sections) may be placed on the deactivated road sections to enhance growing conditions, and then seeded or planted.

Where fill retrieval has been performed, revegetation approaches will depend largely on the surface condition. If the site is favourable for planting and reforestation is an objective, then revegetation may include both conifer planting and seeding to control soil erosion. If the contoured surface is unfavourable for planting (e.g., composed mainly of coarse rock), revegetation may be difficult (Atkins et al. 2001). Seeding may be limited to cross-ditches where soil is exposed. If no reforestation will occur, then the site may be left to revegetate naturally. On sites such as steep gully sidewalls where crossings have been removed, soil bioengineering techniques can be used to stabilize shallow soils before seeding or conifer planting.

Hillslope Rehabilitation Measures

Measures to rehabilitate hillslope disturbances can include headscarp and sidescarp stabilization, runoff management and revegetation of landslides, clearance of woody debris, installation of check dam structures, and revegetation and construction of catchment or deflection structures for destabilized gullies. Methods to stabilize landslide headscarps and sidescarps can include mechanical contouring (where equipment access is possible), installation of soil bioengineering structures (where the instability is relatively shallow), or possible removal of unstable material by blasting.

Soil bioengineering treatments have been widely applied to restore degraded forest sites in British Columbia (see Polster 1997).[5] Soil bioengineering is the use of living plant materials to perform defined functions (Atkins et al. 2001). This differs from biotechnical treatments, such as vegetated riprap or live crib walls, which use both living and dead materials to perform defined functions (Gray and Leiser 1982). Biotechnical treatments are commonly applied in situations where revegetation alone is unable to stabilize the stresses and degrading forces.

In some approaches, stabilization is achieved by rerouting upslope water and (or) re-establishing historic drainage patterns on the hillslope. Runoff management to reduce surface erosion on landslide tracks can be accomplished by:

- channelling surface flow (where channels have not yet developed naturally);
- armouring existing surface channels with rock or bioengineering structures, such as live pole drains or live silt fences; or
- diverting surface flow off the landslide track and onto adjacent stable and non-erodible areas.

In specific cases, containment of surface runoff within closed pipes is also practical. To control erosion, landslide tracks can be revegetated by hydroseeding on steep slopes with harsh soil conditions, dry seeding on more gentle slopes where some organic material and (or) mineral soils remain, or installing soil bioengineering structures, such as brush layers and wattle fences (Figures 18.22 and 18.23).

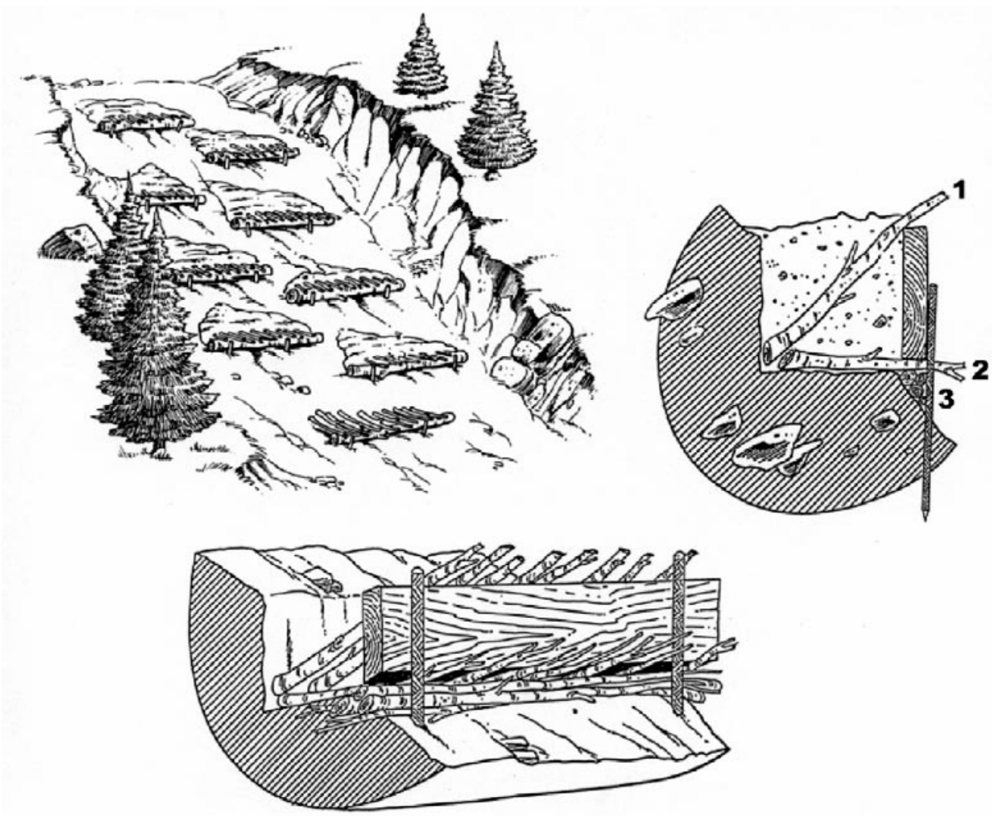

FIGURE 18.22 *Modified brush layers have been developed to treat forest landslides and unstable slopes where normal tree planting would not provide effective stabilization. Cuttings are placed in position 1 under normal conditions, position 2 is used for very dry sites, and position 3 is used when soils are damp (D. Polster, unpublished course materials).*

5 Polster, D.F. 2006. Soil bioengineering for land restoration and slope stabilization. Course materials for training professional and technical staff. Polster Environmental Services Ltd. Unpubl.
Polster, D.F. 2008. Soil bioengineering for land restoration and slope stabilization. Course materials for training professional and technical staff. Polster Environmental Services Ltd. Unpubl.

FIGURE 18.23 *Wattle fences can be used to treat steep slopes where surface ravelling is preventing plant growth. (Photo: D. Polster)*

Soil bioengineering treatments are designed to avoid the need for maintenance, as these methods typically re-establish natural successional trajectories (Atkins et al. 2001); however, where extreme sites are treated, some measure of inspection and maintenance is recommended. Modified brush layers (Figure 18.22) provide an initial treatment of forest landslides where slope and soil conditions preclude normal tree planting as a restoration treatment. Wattle fences (Figure 18.23) are effective for treating wet slides and slumps where ample moisture will ensure good growth of the cuttings. Where sites are very wet, live pole drains (Figure 18.24) are used to provide a preferred flow path for soil water, which enhances stability of the site. Properly applied soil bioengineering treatments can be very effective in treating disturbed sites where conventional planting and (or) seeding are likely to be unsuccessful.

Several measures can aid in gully stabilization. At some sites, the restoration of natural drainage patterns to reduce the concentration of flow can be effective (i.e., where a gully is receiving additional surface or groundwater that has been diverted from its natural drainage). In some areas, reducing flow velocities by installing check dam structures is an effective option to reduce sidewall and channel erosion. For large gullies, engineered check dams constructed of steel and concrete may be required. For smaller gullies, soil bioengineering structures such as live gully breaks (Figure 18.25) can be appropriate, especially where previous events removed all of the vegetation and much of the soil material, leaving poor conditions for the growth of trees. To reduce the volume of possible future debris flow events and (or) to reduce the potential for sidewall erosion, excessive woody debris introduced during harvesting activities (e.g., logging slash) can be removed manually or with the aid of a helicopter and grapple. Hydro-seeding to revegetate sidewall soils is another option if the potential for additional debris flows or floods is low. Structure-based options include debris flow control structures, such as catch basins or deflection berms (VanDine 1996). These types of structures, however, are usually feasible only at sites that can be regularly inspected and maintained, such as on mainline forest roads or at other permanent facilities. Planting is also used to enhance vegetative coverage and provide deeper soil reinforcement. See Atkins et al. (2001) for more information on the rehabilitation of landslide and gullies, including the application of various soil bioengineering techniques.

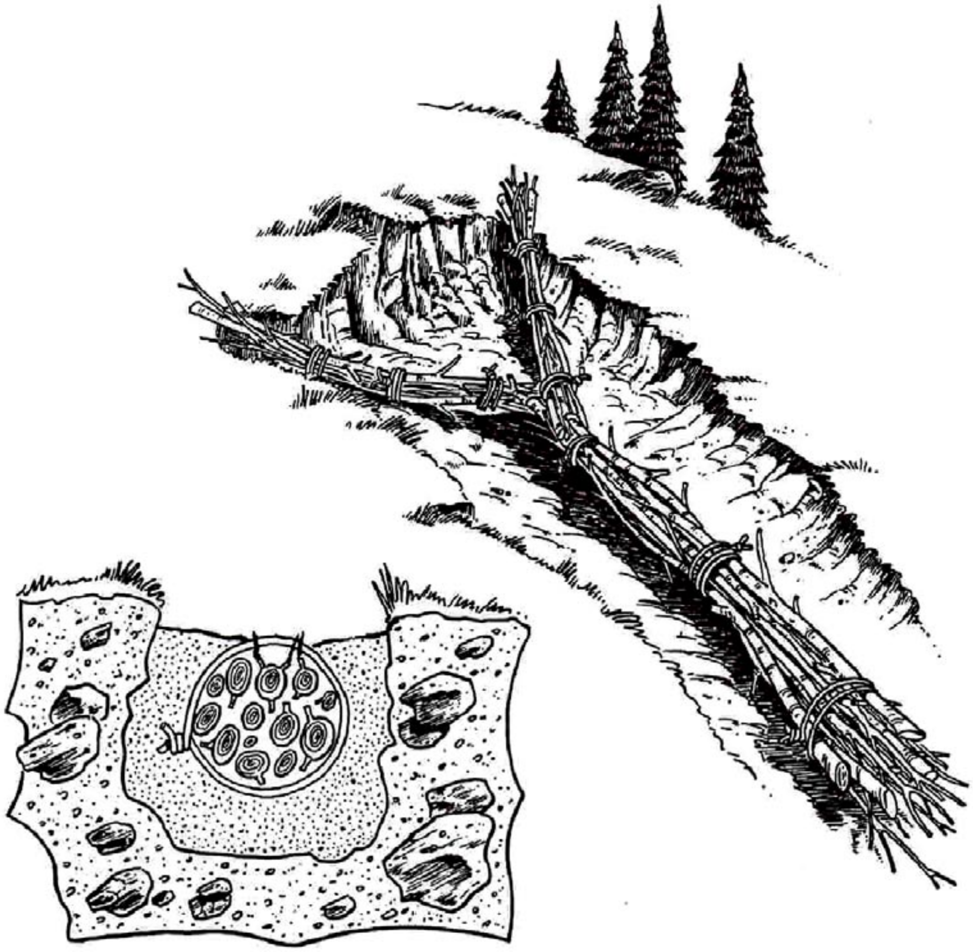

FIGURE 18.24 *Live pole drain schematic (D. Polster, unpublished course material).*

FIGURE 18.25 *Live gully breaks can slow flows down gullies and promote recovery. Right photo shows treatment with water flows. (Photos: D. Polster)*

Riparian and Floodplain Function and Disturbance

Riparian and floodplain area function

Riparian and floodplain areas provide the connection between upslope areas and aquatic ecosystems. The importance of riparian and floodplain ecosystems to the health of aquatic communities has long been recognized (Poulin et al. 2000). Floodplains in watershed systems may vary in size and degree of ecological importance depending on the size of the system and the relative amount of habitat. Stream and riparian ecology is discussed comprehensively in Chapters 13 and 14 of this compendium, and riparian management and effects on function are covered in Chapter 15.

Riparian vegetation has both geomorphic and ecological functions. In alluvial streams, a complex relationship exists between the riparian forest, the large wood debris and litter it supplies, and channel morphology, substrate, and structure. The riparian forest is important for maintaining microclimate as well as channel integrity and structure, which in turn affect the physical quality of aquatic habitat. The root systems of riparian vegetation also provide critical erosion resistance and structural support to streambanks that are in erodible alluvial deposits. Trees falling into the stream but remaining partially rooted in the streambank act as flow deflectors, which slow bank erosion. Downed trees create habitat features and provide cover for fish (Hartman and Bilby 2004; Figure 18.26), and root networks can provide habitat features such as undercut banks (Figure 18.27).

The character and role of the bank-rooting system, and the presence, mobility, and function of wood in streams varies with the type of natural forest that occurs in riparian areas across British Columbia. For example, northern aspen forests have a different rooting structure and bank influence than coastal conifers. The structural role of wood in the channel is also different for an aspen riparian forest than for a riparian forest of large conifers. The size and type of riparian forest that will effectively control bank erosion on alluvial streams depends on the size and energy of the stream. For example, along some small alluvial streams, alders or conifer saplings may be sufficient to stabilize the banks (see Figure 18.3). Large alluvial streams may need fully mature conifer riparian forests with old-growth root characteristics to provide adequate bank erosion resistance and maintain channel stability. Second-growth riparian forests are typically even-aged, high-density stands of tall trees with small rooting masses (Bancroft and Zielke 2002); therefore, these stands lack the necessary root network to resist bank erosion along large alluvial channels (Figure 18.28).

FIGURE 18.26 *Downed trees in streams act as flow deflectors and provide habitat features. Old-growth riparian forest along reach of Nimpkish River, Vancouver Island. (Photo: G. Horel)*

FIGURE 18.27 *Root networks sustain undercut banks, which provide habitat features. Tributary in unlogged area of Doc Creek watershed, Mainland coast. (Photo: G. Horel)*

FIGURE 18.28 *Even-aged thrifty (second-growth) conifer stands do not have the root network needed to control bank erosion along large alluvial streams (compare to Figure 18.26). (Photo: G. Horel)*

On the British Columbia coast, different tree species have different rooting characteristics, and therefore perform differently in providing bank strength and large woody debris in stream channels (depending on channel size). Indeed, the debate amongst restoration practitioners over the role of red alder versus conifers in riparian areas has become polarized. Much of this debate focusses on the functional role and desired densities of red alder. Some practitioners view red alder as an important species for early stages of recovery where conifer regeneration is delayed or unsuccessful. This is because red alder naturally and quickly revegetates disturbed areas and hosts nitrogen-fixing species, which play an important role in the soil nutrient cycle. Other practitioners believe that red alder has a limited effect in nutrient-rich areas (e.g., floodplains), but acknowledge that it is quite beneficial on severely disturbed, nutrient-poor sites such as slide tracks. Red alder may not be as effective as larger conifers in controlling bank erosion because it has a comparatively shallower (and hence weaker) rooting system (Figure 18.29). Furthermore, in many cases, red alder will not provide near-term or long-term functioning LWD because these trees are more easily undercut and broken up, rot more quickly, and are transported more readily than conifers.

Silvicultural perspectives on red alder are also mixed. Some practitioners state that, once established, red alder can suppress conifer growth and delay conifer regeneration, which results in poor vigour, small crowns, inadequate rooting, and poor height-to-diameter ratios (Poulin and Warttig 2005). As well, in certain cases, vigorous competition between alder and conifers may lead to suspended seral states with limited conifer colonization for 200 years or more (W. Warttig, pers. comm., Nov. 2008). Conversely, other practitioners maintain that red alder is an important early seral species, which can enhance the growth of conifers. For example, shade-tolerant species such as western redcedar and hemlock can benefit significantly from a canopy of alder during the early years of growth.

The debate over the role of red alder (or any other tree species for that matter) in any restoration project should be tempered by the restoration goals and objectives, and specifically, by the time frame in which the near- and long-term restoration goals are to be achieved. In some instances, it may be possible to employ the opinions of both camps to reduce the time required for system recovery. Thus, in setting riparian restoration goals, it is important to consider the following.

FIGURE 18.29 *Shallow-rooted alders are easily undercut in alluvial streambanks. This stream in south-central Vancouver Island was logged in the 1950s. (Photo: G. Horel)*

- What is the reference (or most likely) species mix?
- What were the characteristics of the pre-disturbance riparian forest?
- What influence does the riparian forest have on stream channel stability and supply of LWD?
- What is the nature of the disturbance?
- Is channel instability or bank erosion still occurring? If so, to what extent?
- What other site-specific objectives (e.g., species use, ecosystem representation) may be important?

Riparian and floodplain disturbances

Valley floors and floodplains were among the earliest areas developed for settlement, agriculture, and logging because the flat terrain and river channels afforded easy access. Riparian forests were logged, which caused a critical loss of bank erosion resistance; LWD was often removed from the channels; roads and sometimes logging railways were constructed on the floodplains; and streams were diverted or channels altered for transport (sluicing) of logs or other purposes (see Chapter 5, "Forest Practices"). Agricultural development also resulted in the logging and ditching of tributary streams within floodplains, and in some cases introduced sediment and contaminants into the streams. Riparian forests have also been affected by natural disturbances that vary from region to region. For example, large-scale disturbance from wildfire may be part of the natural regime in watersheds in dry climatic regions of the British Columbia interior but not in coastal watersheds. Consequently, alluvial streams with riparian forests that are inadequate or marginally adequate to resist bank erosion are more vulnerable to disturbance from severe floods or major inputs of sediment than undisturbed floodplains.

In many cases, the combined activities of settlement, agricultural development, and logging have had profound effects on channel morphology, including accelerated bank erosion, channel widening, increased sediment transport (Millar 2000), and in some cases, abrupt shifts in channel morphology. For example, Figure 18.30 shows the changes that have occurred in Elk River in Strathcona Park on Vancouver Island. The valley-flat area was harvested in the 1940s (Tredger et al. 1980). A landslide in 1946 increased the sediment load in the river (Mathews 1979), and a headwater diversion in 1957 increased the 2-year return period flow by 20% or more.[6] The pre-diversion channel gradient and discharge plots are near the upper limit of conditions observed on single-thread, gravel-bed channels (see Church 1992 and Figure 18.31). Following the 1946 landslide and the increase in flow, the channel plots (Figure 18.31) above the threshold for a stable, single-thread channel and the river shifted to a braided channel.

The effects of the combined disturbances shifted the channel into a braided configuration, which has undergone little recovery over a period of 50 years (Bailey et al. 2005). These impacts have significantly degraded riparian and channel habitats and resulted in a loss of fish productivity.

Fan disturbances

Fans occur where a confined stream becomes unconfined—for example, where a tributary valley enters a main valley floor, lake, or ocean shoreline (see Chapter 8, "Hillslope Processes"). Fan stability is related to the relative proportion of water and sediment delivered to the fan. The active part of the fan may be all or part of the fan surface. Many fans in British Columbia were essentially formed during deglaciation; thus, contemporary fan-building or fan-eroding activity is limited to only a portion of the fan surface. Further information on fan characteristics and responses to forest development are provided in Wilford et al. 2005 and in Chapter 8 ("Hillslope Processes") and Chapter 9 ("Forest Management Effects on Hillslope Processes").

On an active fan, the forest stores and controls the spread of sediment (Figure 18.32), and its root network is critical in limiting channel bank erosion and stream avulsion (Figure 18.33). Logging the surface of an active fan can thus cause accelerated channel erosion and avulsion because of the loss of root reinforcement and the increased spread of sediment and debris caused by the loss of standing trees. These sites can be difficult to revegetate because treatments such as planting or seeding can be buried by subsequent sediment deposition. Therefore, before any rehabilitation treatments are undertaken on fans, it is essential to have a thorough understanding of the watershed processes above the fan, the rate of sediment delivery, and the consequent level of fan activity.

6 M. Miles and Associates Ltd. 1999. Preliminary assessment of the effects of the Crest Creek and Heber River diversions on channel morphology. Consultant's report prepared for BC Hydro and Power Authority, Burnaby, B.C.

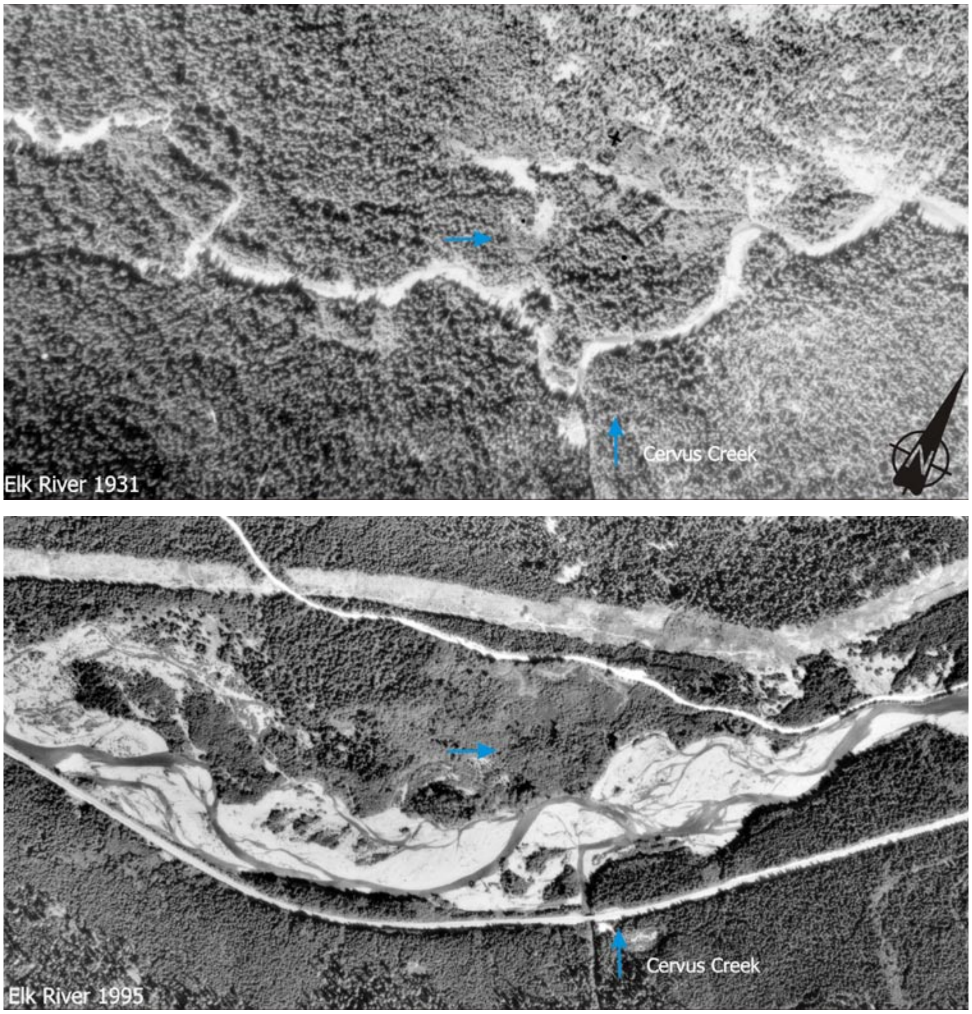

FIGURE 18.30 *The lower section of Elk River on Vancouver Island changed from a single-thread to a multi-thread channel following valley-flat forest harvesting and roading in the 1940s. (Image compilation: M. Miles)*

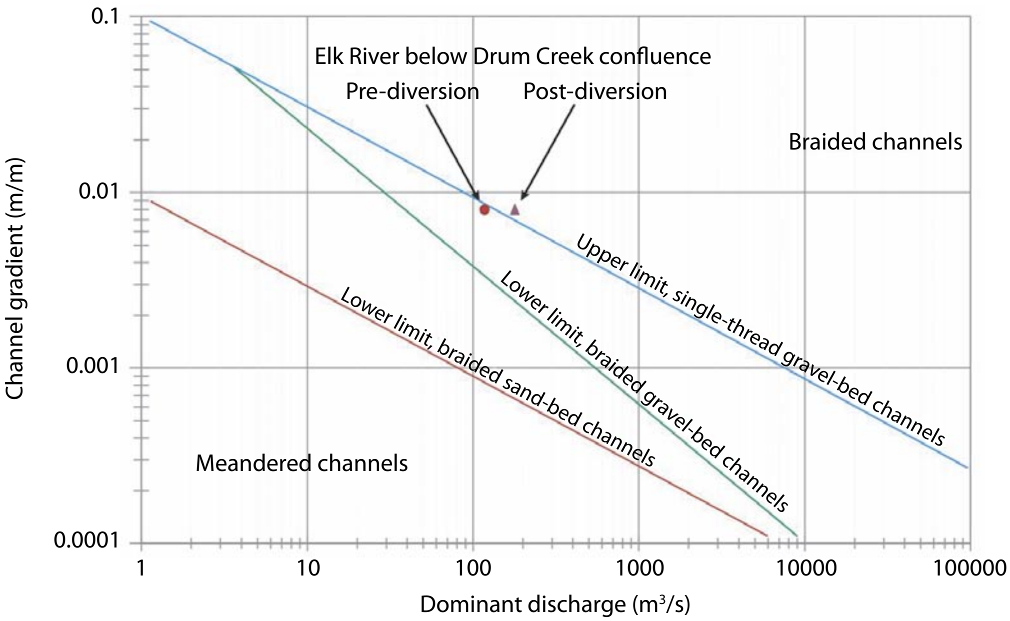

FIGURE 18.31 *The pre-1957 Elk River channel plots near the upper limit of conditions for single-thread channels. Riparian harvest, diversion, and increased sediment yield have caused the channel to "shift" into a braided configuration (M. Miles and Associates Ltd. 1999 [unpublished report] after Church 1992).*

FIGURE 18.32 *On an active fan, the forest limits the spread of sediment and debris. (Photo: D. Wilford)*

FIGURE 18.33 *The root network is critical in limiting bank erosion and channel avulsion on active fans. (Photo: D. Wilford)*

Riparian and Floodplain Rehabilitation Measures

This section outlines a few of the many restoration approaches used for riparian forests, and the revegetation techniques employed on floodplain gravel bars. Measures for bank erosion protection are discussed below in the section on "Stream Channel Restoration." As previously mentioned, opinions about appropriate riparian rehabilitation measures vary among practitioners and depend on restoration goals. The following publications provide information on the wide range of riparian restoration measures that may suit a particular application or watershed (Table 18.1).

Riparian and floodplain rehabilitation measures are frequently used for the following purposes.

- Stabilizing gravel bars in streams with excess erosion of logged alluvial channel banks, or which have been affected by sedimentation from development-related landslides and upslope erosion.
- Accelerating the trend toward old-growth characteristics in second-growth coniferous or mixed riparian stands to provide functioning LWD and to restore biodiversity and ecological function in riparian habitats.
- Promoting conversion from disturbance-generated stands (e.g., red alder) on floodplains or fans to conifer-dominated stands with a species mix that is more consistent with the pre-disturbance riparian forest as a means to achieve natural levels of erosion resistance in alluvial streambanks and to provide long-term sources of functioning LWD.

If available, historic air-photo series can be used to identify characteristics of the pre-disturbance riparian forest and stream condition and the subsequent response to logging or sedimentation.

Treatment of riparian stands

Where logged riparian forests have regenerated extensively to alder, planning of treatments to promote conversion to conifers must be done with care. Wholesale removal of the alder will simply recreate the original disturbance; therefore, it is not a recommended treatment.

Example treatments of alder-dominated riparian forests include the following:

TABLE 18.1 *Riparian restoration references*

Reference	Title
Bancroft and Zielke 2002	Guidelines for Riparian Restoration in British Columbia: Recommended Riparian Zone Silviculture Treatments
Bentrup and Hoag 1998	The Practical Streambank Bioengineering Guide: User's Guide for Natural Streambank Stabilization Techniques in the Arid and Semi-arid Great Basin and Intermountain West
Montgomery et al. [editors] 2003	Restoration of Puget Sound Rivers
Muhlberg and Moore 1998	Streambank Revegetation and Protection: A Guide for Alaska
Polster 2001	Streambank Restoration Manual for British Columbia
Poulin and Warttig 2005	Learning by Doing: Post-Treatment Responses Noted at Four British Columbia Riparian Restoration Sites
Taccogna and Munro [editors] 1995	The Streamkeepers Handbook: A Practical Guide to Stream and Wetland Care
U.S. Department of Agriculture, Natural Resources Conservation Service 1998	Stream Corridor Restoration: Principles, Processes and Practices
U.S. Department of Agriculture, Natural Resources Conservation Service 2007	Stream Restoration Design
Washington State Aquatic Habitat Guidelines Program 2003	Integrated Streambank Protection Guidelines

- Where conifers are present in the stand, a portion or patch of overstorey alders can be felled or girdled to increase light to the conifers.
- Where few or no conifers are present in the stand, conifers can be planted in conjunction with felling or girdling some of the alders.

Additional measures can be used to temporarily improve riparian and stream habitat until natural recovery occurs. These include:

- placing some of the felled trees in channels that are deficient in LWD; and
- in thrifty conifer stands, topping or scarring trees to promote mortality and create standing dead trees for biodiversity.

Although the degree of success achieved with these treatments may not be fully known for many years, early results from treated sites are promising (Poulin and Warttig 2005).

Gravel bar revegetation

Live gravel bar staking (Figure 18.34) is used to initiate natural successional processes on gravel bars that

FIGURE 18.34 *Live gravel bar staking can be used to initiate natural successional processes on gravel bars that form from excess sediment accumulation associated with development-related landslides or erosion. (Image: D. Polster)*

formed as a result of excessive bedload accumulation. The live staking locks the gravel in place and provides an area where flood flows can overtop and deposit additional sediment. As the treated gravel bars become more terrestrial, the stream thalwag deepens. Natural successional processes initiated by live gravel bar staking will eventually lead to the development of highly productive riparian forests. By way of example, Figures 18.35–18.41 show a site on Vancouver Island's San Juan River where live gravel bar staking was used to transform a bare, low-elevation gravel bar to a productive riparian habitat where forest species are starting to appear.[7]

FIGURE 18.35 *Live gravel bar staking on the San Juan River, March 12, 1998. The red arrow indicates a reference cottonwood. (Photo: G. Switzer)*

FIGURE 18.36 *Live gravel bar staking starting to grow (May 19, 1998). (Photo: D. Polster)*

FIGURE 18.37 *Live gravel bar staking traps small woody debris, creating a flow disruption and allowing sediment to collect (March 12, 1999). (Photo: D. Polster)*

FIGURE 18.38 *A total of 80 cm of new sediment was deposited on this gravel bar on the San Juan River (March 12, 1999) during the first high flows following treatment. (Photo: D. Polster)*

7 Polster, D.F. 2008. Soil bioengineering for land restoration and slope stabilization. Course materials for training professional and technical staff. Polster Environmental Services Ltd.

FIGURE 18.39 *The cuttings planted on this gravel bar on the San Juan River in 1998 continue to grow and provide habitat for later successional species (June 2, 2006). (Photo: D. Polster)*

FIGURE 18.40 *Live gravel bar staking on the San Juan River has resulted in the accumulation of substrate on the gravel bar surface (right) and a deepening of the river channel (left) (June 2, 2006). (Photo: D. Polster)*

FIGURE 18.41 *Understorey on the San Juan River gravel bar that was staked in 1998. The occurrence of riparian species, including cow parsnip and salmonberry, indicate that successional processes are occurring on the site (June 2, 2006). (Photo: D. Polster)*

STREAM CHANNEL RESTORATION

Stream channel restoration may be carried out for a number of reasons. For example, a need may exist to improve the quality of aquatic habitat or create additional habitat (see Chapters 13–15 for detailed discussions of aquatic ecology and management). In some cases, restoration may focus on increasing the extent of fish access, especially where fish passage has been impeded by artificial barriers. Stream channel restoration measures can also be implemented to protect stream-adjacent infrastructure, property, or sites of high ecological or cultural value that are threatened by channel instability or erosion.

Numerous treatments can be applied to stream channels, including:

- channel bank erosion control measures;
- instream works to improve fish habitat;
- off-channel works to create or enhance fish habitat;
- replacement of road drainage structures that impede fish access;
- removal of unneeded streambank revetments, which reduce floodplain connectivity or prevent channel shifting; and
- constructing engineered stream works to control streamflow, sediment, and other channel processes.

An essential first step in planning stream channel restoration activities is to understand the geomorphic, hydrologic, and hydraulic behaviour of the stream system. This is paramount, as investments in stream treatments may be lost if treatment measures are inadequate to withstand stream processes or are inappropriate for the site. In particular, high-energy streams, active fans, and unstable alluvial channels are high-risk sites for instream treatments, which can result in treatment failure. For example, even very large boulder structures are subject to scour, which causes the rocks to sink and become buried in the channel bed (see Figures 18.42 and 18.43, below; also Miles 1998).

FIGURE 18.42 *Coquihalla River, 1984: these boulder structures were constructed along the Coquihalla River using the largest rocks that could be moved with highway construction equipment. (Photo: M. Miles)*

FIGURE 18.43 *Coquihalla River, 1991: Local scour associated with flood flows caused the boulders to sink and become buried in the channel bed. (Photo: M. Miles)*

Specific restoration objectives should be established at the outset and should consider the following factors.

- What is the intended life of the treatment (short or long term)?
- What are the potential risks to the treatment from geomorphic and hydrologic factors, such as landslides, channel instability, erosion, scour, and sediment deposition?
- What is the likelihood that the measures will achieve the stated objectives?
- What maintenance or retreatment activities are required to ensure that the measures continue to perform as intended?
- Will future funding be available for maintenance?
- Will the site be accessible in the future for maintenance and performance monitoring purposes?

Performance evaluations of instream rehabilitation measures have not been routinely conducted for watershed restoration projects in British Columbia; however, a few studies conducted elsewhere have provided important feedback on the performance of these measures. For example, a study in southern Alberta investigated the factors that affected the performance of instream structures constructed by the "Buck for Wildlife" program (see Fitch et al. 1994). The results indicated that instream structures commonly failed in river reaches that were vertically or laterally unstable, were transporting significant quantities of bedload, and (or) had alluvial banks that were less than 2 m high. In British Columbia, these characteristics commonly occur on alluvial channels that have been destabilized by logging activity. Similar studies have been undertaken to evaluate the efficacy of the BC Habitat Conservation Fund's instream restoration projects (Hartman and Miles 1995), and to develop compensatory trout habitat for mine sites (Hartman and Miles 2001).

Channel Bank Erosion Control Measures

Channel bank erosion can result from natural causes, removal of riparian vegetation, upstream changes to the channel, or a combination of these factors. Control measures can be used to:

- protect adjacent property or infrastructure from bank erosion,
- reduce sediment input from sources that are causing channel changes or habitat degradation, and
- restore channel bank stability by re-establishing bank vegetation on sites where vegetation removal has increased the rate of erosion and sediment introduction to the stream.

As previously mentioned, selected erosion control measures should be suitable for the stream characteristics and the measures' required design life. Three common erosion control measures are (1) rock armouring (also called "revetment" or "riprap"), (2) vegetation treatments, and (3) engineered logjams.

Rock armouring

Rock armouring is commonly used to reduce erosion hazards around stream crossings or along road encroachments. It is an effective form of erosion control for high-energy streams, and if properly designed, is essentially a permanent installation. However, this treatment requires an understanding of potential future channel morphology evolution and appropriate hydraulic analysis. Rock armour can fail to function as intended if applied improperly, or it can create increased instability in adjacent sections of the channel. A loss of riparian function and habitat complexity can also occur where rock armour is used over long bank lengths. These shortcomings can be overcome by designing rock armouring in conjunction with revegetation techniques and other habitat measures (see below). Interstitial spaces in the rock armouring can provide cover for fish fry when suitably coarse material is used. If it includes spurs or other hydraulically rough features, rock armouring can also create pools and other useful habitat features (see Lister et al. 1995; Schmetterling et al. 2001; Quigley and Harper [editors] 2004; Figure 18.44). Other measures can include varying the alignment of the streamside edge of the armour, and anchoring LWD into the rock mass (Figure 18.45).

Live bank vegetation techniques for erosion control

Live bank protection (Figures 18.46 and 18.47) uses vegetation cuttings to support eroding streambanks. This measure is of use only where soil moisture conditions are sufficient for the cuttings to grow and develop into riparian cover. In addition, careful attention to detail at the upstream end of a soil bioengineering treatment is required to ensure that the structures are durable through periods of high flow.

Engineered logjams

Engineered logjams (ELJs) are constructed by cabling and anchoring logs in configurations that are

FIGURE 18.44 *Hydraulically rough riprap formed of large rock and short spurs can be used to enhance fisheries habitat values along short sections of the riprap. (Photo: M. Miles)*

FIGURE 18.45 *Habitat complexity was added to this channel by varying the alignment of the streamside face of the revetment and by anchoring large woody debris into the revetment. (Photo: G. Horel)*

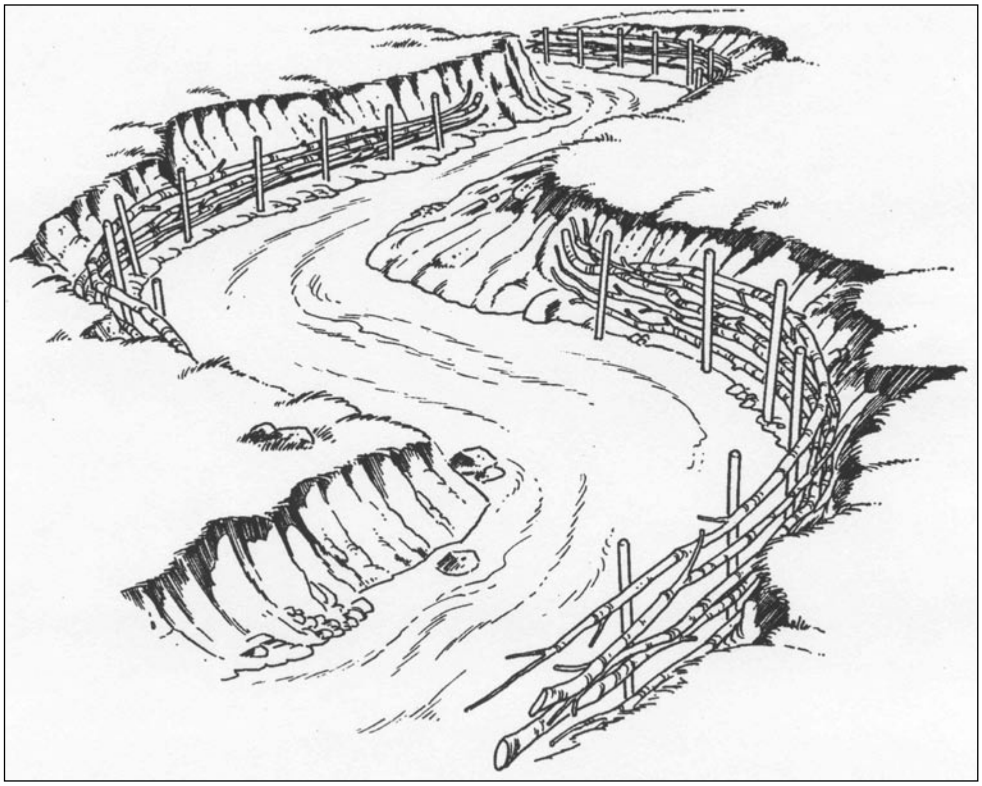

FIGURE 18.46 *Live bank protection can be used to support eroding streambanks. This drawing shows installations without backfill. (Image: D. Polster)*

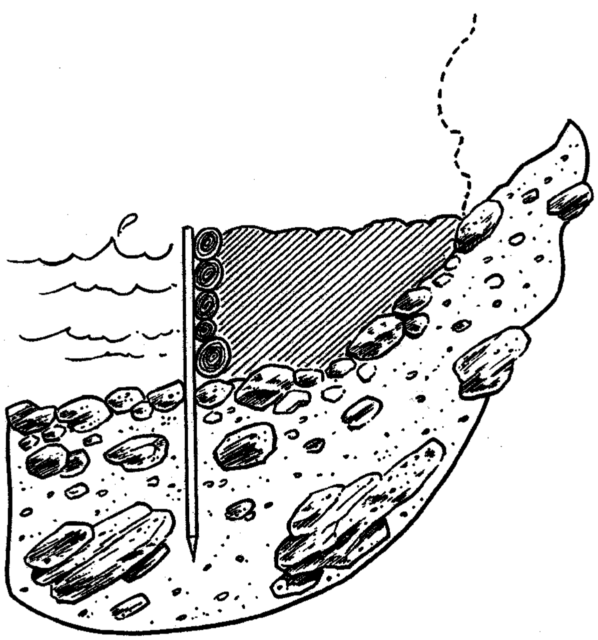

FIGURE 18.47 *Cross-section of live bank protection showing normal backfill. Note that the bank is trimmed back to provide the backfill. (Image: D. Polster)*

intended to mimic natural logjams. This measure is becoming increasingly popular in stream restoration projects because it combines bank erosion protection and habitat features. An ELJ can also be used strictly for habitat applications (see "Instream and Off-channel Measures" below). As an erosion protection measure, it is often placed at the eroding outside bends of streams, in locations where wood accumulations would not be found naturally. An ELJ is not designed as a permanent structure because the wood eventually decomposes and the structure comes apart; therefore, the required design life and liability of the ELJ must be considered (see discussion below). If the value to be protected is permanent infrastructure, a more durable treatment (e.g., rock armour) may be more appropriate.

In a review of ELJ performance in Washington State, Southerland and Reckendorf (2008) found that of 43 installations reviewed, 8 failed completely and another 22 were compromised in some way. When ELJs are intended primarily for erosion control, these structures should be engineered to resist shear forces, scour, buoyancy, and flanking (eroding behind the structure). An ELJ for erosion control can be effective when it is intended only as an interim measure until other processes take hold (Figure 18.48).

In streams used for recreational purposes, liabilities can be associated with ELJ construction. An ELJ may pose a hazard to swimming, tubing, and rafting, as can the cable and other materials left behind in the stream when the wood decomposes.

Instream and Off-channel Measures

Numerous instream and off-channel measures can be used to achieve specified restoration goals in British Columbia. Common instream measures include:

- adding habitat elements such as LWD or boulders;
- constructing features such as undercut banks and ponds;
- rearranging or removing existing logjams to improve fish passage;
- widening choke points where debris jams regularly occur and impede fish access;
- removing old dams or other artificial barriers;
- realigning channels that were previously ditched or diverted;
- altering beaver dams to allow fish passage where it has been impeded by the dam;
- providing enticements to beavers to build dams at certain locations, to store water for habitat, or to avoid damming up drainage structures;
- removing excess sediment in aggraded channels; and
- placing gravel in streams that are sediment-deficient (e.g., where natural sediment supply is cut off by dams, works associated with drainage structures, or other barriers).

Off-channel measures are frequently used to create additional habitat. Common treatments include:

- reopening and enhancing abandoned flow channels on fans or floodplains;
- creating new channels or ponds on a floodplain or a fan; and

FIGURE 18.48 *A series of engineered logjams placed to reduce flow velocities at the base of the embankment allows vegetation to become established on the slopes. (Design by M. Sheng; site supervision by M. Wright; photo: G. Horel)*

- constructing ponds or opportunistically remediating features such as flooded gravel pits or quarries on adjacent terrain where it is feasible to construct fish access from the stream.

Extensive information is available on approaches to instream and off-channel restoration measures (see Tables 18.2 and 18.3). Many case studies of instream and off-channel projects have also been used in British Columbia to rehabilitate or create replacement fish habitat (e.g., Underhill [editor] 2000; Cleary and Underhill [editors] 2001).

When designing and constructing instream and off-channel rehabilitation measures, it is important to fully understand the behaviour and habitat requirements of the fish (and [or] other species) in the restoration area of interest, as well as the natural processes that shape and maintain the habitat and the frequency of disturbances. Different species and different life stages of fish require different habitat features within the stream. A particular kind of fish at a particular age may use different habitats during the day and night. For example, during winter, 1- and 2-year-old steelhead in the lower reaches of the Chilliwack River were observed to occupy large collections of rootwads during the day but move into wide, shallow riffle sections adjacent to the rootwads at night (G. Hartman, field observations). Consequently, built habitats must fit the age of, and critical time periods for, the species of interest in the restoration area. In a multi-species situation, it may be most desirable to restore a stream channel to conditions that mimic a productive natural stream section.

TABLE 18.2 *Stream restoration references*

Authors	Title
Alberta Transportation and Utilities 2009	*Fish Habitat Manual: Guidelines and Procedures for Watercourse Crossings in Alberta*
Biedenharn et al. 1997	*The WES Stream Investigation and Streambank Stabilization Handbook*
Fischenich 2001	*Stability Thresholds for Stream Restoration Materials*
Hunter 1991	*Better Trout Habitat: A Guide to Stream Restoration and Management*
Newbury and Gaboury 1993	*Stream Analysis and Fish Habitat Design: A Field Manual*
Saldi-Caromile et al. 2004	*Stream Habitat Restoration Guidelines*
Slaney and Zaldokas 1997	*Fish Habitat Rehabilitation Procedures*
The River Restoration Center 2002	*Manual of River Restoration Techniques*
U.S. Department of Agriculture 2007	*Stream Restoration Design*

TABLE 18.3 *Stream restoration web resources*

Title	URL
eWater CRC Catchment Toolkit	www.toolkit.net.au/
National Center for Earth Surface Dynamics Stream Restoration Toolbox	www.nced.umn.edu/content/tools-and-data
River Restoration Northwest	www.rrnw.org
Streamline Watershed Management Bulletin	www.forrex.org/streamline/streamline.asp
The Nature Conservancy	www.nature.org/initiatives/freshwater/conservationtools/
U.S. Army Corps of Engineers. Engineer Research and Development Center Technical Notes	http://el.erdc.usace.army.mil/publications.cfm?Topic=TechNote&Code=emrrp
U.S. Forest Service Stream System Technology Centre	www.stream.fs.fed.us
U.S. Natural Resources Conservation Service (National and Oregon)	www.nrcs.usda.gov/ www.or.nrcs.usda.gov/technical/technology.html

Instream treatments

Many kinds of instream treatments are used to improve habitat. In coastal streams, woody structures (LWD) or boulder groups are commonly used to provide cover and mimic channel conditions found in old-growth streams. Remedial measures may incorporate other engineered stream works to address site-specific problems; for example, instream treatments are used to maintain flow to drainage structures, to split stream flows, to create channel bed roughness that reduces flow velocity, or to limit bedload mobilization and transport.

Large woody debris in a stream reach can come from several natural sources depending on the physical processes that occur in the watershed and on the transport capacity of the stream. Natural sources of LWD include adjacent streambanks, areas upslope from landslides or debris flows that deposit into the stream, and transport from stream reaches farther up the watershed (see Chapter 10, "Channel Geomorphology: Fluvial Forms, Processes, and Forest Management Effects").

To achieve the greatest long-term success of installed LWD structures, it is necessary to understand the source of wood that is deposited in streams and the manner in which the wood functions in different stream types. Several information sources are available on designing stream rehabilitation structures. For example, D'Aoust and Millar (1999, 2000) provide guidelines for determining ballasting requirements, and Herrera Environmental Consultants Inc. (2006) provides additional advice on constructing multi-level or complex engineered logjams.

Installations that conform to natural LWD occurrence are most likely to achieve success in providing habitat and influencing geomorphic processes. In small streams, LWD may extend partially into or fully across the channel, or may form steps or flow diversions. In low-energy streams, LWD can persist until it decomposes and breaks apart. In large alluvial streams, natural LWD typically forms jams that aggregate on bars and then become mobile to disperse and reform farther downstream. These jams create channel complexity and form habitat features such as scour pools. If the jams persist for periods of time, they may also protect gravel bars, and allow revegetation to occur downstream of the jam (Figure 18.49). In high-energy streams confined by non-alluvial banks, LWD may be highly mobile and have little influence on channel morphology or habitat features.

FIGURE 18.49 *Large woody debris accumulations deflect flow, which can create scour pools. Large woody debris also protects the gravel bar behind, allowing revegetation to occur. (Photo: G. Horel)*

Large woody debris installations are likely to be most durable in streams with low transport capacity. Additional considerations in using LWD for instream treatments are the source of natural LWD supply and the length of time that the installation may be required to function before natural LWD recruitment can take place. For example, if the main source of LWD to a stream reach is the adjacent banks, then the LWD installation will need to persist until the adjacent riparian forest is of sufficient size and species composition to provide functioning LWD.

Depending on the characteristics of the stream, maintenance or retreatment may be necessary to keep the LWD installation functioning for the intended design life. Figures 18.50 and 18.51 show LWD structures that have been cabled to trees growing on the bank or anchored in place using cables and large rocks.

Similar to ELJs (see "Engineered logjams" above), liability issues may be associated with cabled LWD structures and with leaving cables and other non-natural material in the stream when the structures decompose. For example, concern surrounds the possible movement of introduced wood downstream to bridges, reservoirs, control gates, or other structures. In these cases, other instream measures may be more appropriate, such as placing individual boulders or drilling and cabling boulders together in strings to mimic LWD function.

Stream crossings

Road deactivation at stream crossings most often includes full removal of the crossing structure. In the case of wood bridges or log culverts, this includes removing sills and cribs that form part of the footing structures. In some cases, it may be preferable to leave all or part of the footing structures in place, especially if the stream channel has adapted to the structure and beneficial habitat features have developed. Figure 18.52 shows an example of an old log crib that has collapsed into the stream. A scour pool developed in front of the structure and a gravel bar developed on the downstream side. Removing the structure would cause the gravel bar to remobilize and might also result in the loss of the scour pool.

Where existing drainage structures impede fish passage, it is sometimes possible to create fish access by constructing fish ladders around the structure or creating stepped ponds up to the outlet. Often, restoring fish access requires replacing the struc-

FIGURE 18.50 *This large woody debris structure was constructed to narrow and deepen a degraded channel and provide fish habitat. (Photo: M. Miles)*

FIGURE 18.51 *Large rocks and cables can be used to anchor large woody debris placed in channels for habitat improvement. (Site work by W. Pollard; photo: G. Horel)*

FIGURE 18.52 *An old crib has distorted and settled, creating a scour pool in front of the logs; a gravel bar has developed on the downstream side of the collapsed crib. (Photo: G. Horel)*

ture altogether. Fish access can also be improved by removing or modifying natural barriers. Before undertaking any work of this nature, the ecological implications of providing certain species (e.g., invasive species) with increased access should be thoroughly considered.

Off-channel measures

Off-channel habitat measures (e.g., Figure 18.53) located away from high-energy flows in the main stem provide refugia for fish and other organisms during high flows and reduce the likelihood of flood damage to the remedial measures. These structures are typically excavated in areas of floodplains where tributary inflow or valley wall seepage can provide a source of suitable water (e.g., groundwater). One of the benefits of using groundwater as a water source for off-channel habitat is that it is frequently cooler in the summer and warmer in the winter than water in adjacent main-stem channels. Groundwater or tributary water may also be, at least seasonally, less turbid than main-stem river water. In some situations, it can be possible to construct gravel platforms in off-channel areas to provide spawning habitat. Woody debris can also be incorporated into these structures to provide refuge cover, and gravel introduced to stream channels[8] to provide spawning habitat if, for example, the upstream supply has been cut off by dam construction. Sometimes, with the use of sites such as old quarries or gravel pits, it is possible to develop off-channel habitat if suitable groundwater conditions exist (Figures 18.54, and 18.55). Before developing such off-channel habitat, however, it is important to determine the site's suitability by using test excavations or pump tests to confirm water availability and quality (particularly dissolved oxygen levels).

FIGURE 18.53 *Off-channel development has the benefit of providing useful habitat in areas with some protection from flood damage. (Photo: M. Miles)*

8 This type of project requires hydrologic and hydraulic calculations to determine the size of the bed material the stream can move (i.e., substrate), and potential transport rates. Free programs are available to assist with this analysis, such as WinXSPRO (available at www.stream.fs.fed.us/publications/software.html) or HEC-RAS (available at www.hec.usace.army.mil/software/hec-ras/).

FIGURE 18.54 *Off-channel habitat created in groundwater-fed gravel pit and connected to Taylor River, south-central Vancouver Island. (Site work by M. Wright; photo: G. Horel)*

FIGURE 18.55 *Channel excavated to connect gravel pit to Taylor River. (Site work by M. Wright; photo: G. Horel)*

The final component of restoration is monitoring. This step enables the incorporation of adaptive management into the restoration process and is essential to achieve success in watershed restoration projects (Hartman 2004). Assessing the performance of projects over relevant time periods also provides important information for use in future projects designed to protect aquatic resources (Hartman and Miles 1995; Harper and Quigley 2000; Gustavson and Brown 2002;). Techniques to evaluate the performance of projects can be varied and complex. Koning et al. (1998) provided a review of the techniques available up to 1998. Gaboury and Wong (1999) provided a discussion of monitoring and effectiveness evaluations within the context of watershed restoration. See Corner et al. (1996), Wilford and Lalonde (2004), and the references listed in Table 18.4 for discussions of various monitoring strategies.

Providing information on experimental designs, techniques, and monitoring is an important part of improving restoration projects (Keeley and Walters 1994). Ideally, monitoring strategies and effectiveness evaluation criteria are determined at the project outset and incorporated throughout the planning and implementation phases. The identification of key field indicators and the frequency or level of detail to be monitored is of critical importance. Unfortunately, although effectiveness evaluation may be the greatest source of restoration information[9] for adaptive management, few funding agencies are willing to commit to years of monitoring.

To truly understand the effectiveness of restoration projects and rehabilitation treatments, it is critical to evaluate the effectiveness of the work against the original objectives and overall goal(s). For example, if the objective is to increase the number of fish in a system or stream reach, then this is the variable that should be quantified (before and after treatment).

In general, monitoring of restoration projects should:

- be done independently of the original design and construction;
- check the physical integrity of the works against the intended design life;
- determine whether the works are meeting the original objective; and

TABLE 18.4 *References for monitoring and effectiveness evaluations*

Authors	Title
Bryant 1995	*Pulsed Monitoring for Watershed and Stream Restoration*
Gaboury and Wong 1999	*A Framework for Conducting Effectiveness Evaluations of Watershed Restoration Projects*
Harper and Quigley 2005	*No Net Loss of Fish Habitat: A Review and Analysis of Habitat Compensation in Canada*
Harris 2005	*Monitoring the Effectiveness of In-stream Substrate Restoration*
Kondolf 1994	*Learning from Stream Restoration Projects*
MacDonald et al. 1991	*Monitoring Guidelines to Evaluate Effects of Forestry Activities on Streams in the Pacific Northwest and Alaska*
Palmer et al. 2005	*Standards for Ecologically Successful River Restoration*
Pearson et al. 2005	*Monitoring and Assessment of Fish Habitat Compensation and Stewardship Projects: Study Design, Methodology and Example Case Studies*
Roni [editor] 2005	*Monitoring Stream and Watershed Restoration*
Roni et al. 2005	*Habitat Rehabilitation for Inland Fisheries: Global Review of Effectiveness and Guidance for Rehabilitation of Freshwater Ecosystems*

9 Polster, D.F. 2008. Soil bioengineering for land restoration and slope stabilization. Course materials for training professional and technical staff. Polster Environmental Services Ltd.

- determine whether unintended consequences have occurred as a result of the rehabilitation treatments (e.g., unanticipated scour associated with instream measures, or unanticipated windthrow in riparian treatments).

EMERGING TOPICS IN WATERSHED RESTORATION

Several topics of interest or concern have emerged in the field of watershed restoration. This section briefly examines six such emerging topics: (1) alien invasive species, (2) rehabilitation of areas affected by wildfire, (3) rehabilitation of areas affected by the mountain pine beetle infestation, (4) restoration designs for long-term site nutrient balances, (5) liability, and (6) inconsistencies in design methodologies.

Alien Invasive Species

The introduction and spread of alien invasive species is a critically important issue in most restoration projects (Polster et al. 2006). Although non-native fish can be introduced to streams (not necessarily by restoration activities), the following discussion focusses on invasive plants. Invasive plant species can be introduced to a site by using poor-quality seed during revegetation of road cuts and fills, by using equipment or vehicles that have been working in infested areas, or by using contaminated hay. The use of poor-quality seed during revegetation (grass seeding) is particularly problematic. Species such as Canada thistle (*Cirsium arvense*) are often found in low-quality seed. Therefore, many practitioners purchase "customer specified Canada No. 1 mix" seed from reputable dealers and avoid using seed labelled "forage" or "ground cover," as the standards of purity associated with those designations are often significantly lower.

Some species that are commonly used for reclamation of disturbed sites can also become invasive. Orchardgrass (*Dactylis glomerata*), crested wheatgrass (*Agropyron cristatum*), and reed canarygrass (*Phalaris arundinacea*) can all become serious pests in some parts of the province. Care should be exercised where these species are used so that these plants do not establish and outcompete other species that would compose a balanced ecosystem. The Invasive Plant Council of BC (www.invasiveplantcouncilbc.ca/) provides detailed information on invasive species and treatments that are available throughout the province.

Invasive species can also be moved onto a restoration site by contaminated equipment that has worked in infested areas. Seed of species such as marsh plume thistle (*Cirsium palustre*), knapweeds (*Centaurea* spp.), and oxeye daisy (*Leucanthemum vulgare*) is easily transported in the mud on the tracks of excavators or other equipment. Sometimes weed seeds are moved by ATVs and other motor vehicles. Where ATVs are used on deactivated roads, care must be taken to ensure the vehicle is clean (i.e., no weed seeds in any mud on the vehicle or flower parts containing seed caught on the vehicle). Where hay is used for sediment control or as mulch (e.g., erosion mitigation after wildfires), care must be taken to ensure that it is weed-free. Inexpensive hay can be seriously contaminated with various invasive species. For example, toadflax (*Linaria* spp.), orange hawkweed (*Hieracium aurantiacum*), and scentless mayweed (*Matricaria perforata*) are commonly found in low-quality hay. Once established in an area, invasive species are difficult to control.

The management of alien invasive plants can be difficult and costly, and rarely has a successful conclusion. Millions of dollars are spent annually in controlling alien invasive species in British Columbia. In planning restoration projects, the most effective strategy is to prevent alien invasives from establishing. Part of this strategy is to become familiar with the common invasive species that might occur on local sites, and to then use appropriate eradication methods if these plants appear (www.invasiveplantcouncilbc.ca; see the Targeted Invasive Plant Solutions [TIPS] series on "Resources" web page). The Invasive Plant Council of BC provides information on common invasive species by region. Where invasive species have been established for several years, restoration plans often include the eradication of plants in the least-infested areas first, and then work towards areas of greatest infestation. By controlling the spread of these plants, the harmful effects can be minimized. Persistence is the key to effective invasive species management.

Rehabilitation of Areas Affected by Wildfire

The province of British Columbia has a legal requirement to repair damage resulting from fire-fighting operations. Therefore, post-fire rehabilitation is commonly taken to mean the rehabilitation of fireguards, camps, access routes, and other scars left by fire-fighting operations. Rehabilitation also includes re-seeding fireguard zones after contouring and drainage restoration activities. In 2004, the B.C. Ministry of Forests Protection Branch (now Wildfire Management Branch) updated its fire site rehabilitation manual to better plan for and address post-fire rehabilitation. Pike and Ussery (2006, 2007) also published two documents that address key points to consider when planning for post-wildfire rehabilitation.

From a broader perspective, the risk of erosion and flooding after a watershed has been burned should be considered. In the aftermath of wildfires, large areas may be left bare and vulnerable to erosive forces. Under certain circumstances, these burned areas have a greatly increased hazard of overland flow occurring during rain events, and an associated hazard of flooding, erosion, and sedimentation from the catchment as a whole. Considerable experience with wildfire effects in the United States has led to the general recognition of a "fire–flood–erosion" sequence. Consequently, assessments are undertaken immediately after the fire on sites determined to be at risk from floods and erosion, and rehabilitation of burned hillslopes is prescribed.

Numerous rehabilitation measures have been used over the last couple of decades (see Napper 2006). Robichaud et al. (2000) documented and assessed the usefulness of these methods; however, many rehabilitation efforts are applied in haste, so a full assessment of the costs and effectiveness is not possible.

The more intensive post-fire rehabilitation methods involve installing contour barriers across steep hillslopes. The barriers are intended to slow overland flow and trap eroded soil. Contour logs are created by felling trees, fixing them in place on the contour using wooden stakes, and filling the gaps beneath the logs by excavating above the log. The installation of contour barriers requires significant financial resources and effort, and involves considerable disturbance of the hillslope. Alternatively, straw wattles (long "sausages" of straw) may be used. These barriers mould to the slope surface easily and can filter water that flows slowly through them.

Another very expensive rehabilitation method, used on highly vulnerable slopes close to roads, is hydro-mulching or hydro-seeding. This involves spraying a slurry of seeds, mulch, and a sticking agent (or tackifier) onto the soil surface. Probably the least expensive rehabilitation method (aside from doing nothing) involves simply seeding with a mixture of quick-growing grass and pasture seeds, often of annual cover crops. These mixtures are applied from the air by fixed-wing aircraft or helicopter at rates of 5–10 kg of seed per hectare. This option is quick and cheap but may be of little use if rains arrive before a good cover crop establishes. The seed mixtures are also a possible source of alien invasive species (see discussion above).

The most successful and cost-effective rehabilitation methods involve mulching. The quickest of these is straw mulching, in which large stocks of straw are chopped and then dropped from a helicopter, with the downdraft helping to spread the mulch across the landscape. As with seeding, this method carries the risk of introducing alien plant and weed seeds. Another mulching method involves chipping trees on-site and distributing the mulch across the burned slope. These methods mimic the effect of needle-fall, which occurs naturally when trees are killed by a ground fire but the foliage is not consumed. In the weeks and months following the fire, the dying foliage falls from the canopy and creates an even ground cover, which is highly effective in protecting slopes from erosion (Robichaud et al. 2000; Giest and Scott 2006).

Rehabilitation of Areas Affected by the Mountain Pine Beetle Infestation

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins [MPB]) has killed and will continue to kill pine trees over huge tracts of forest across British Columbia. This has the potential to both directly and indirectly affect watershed processes and values. For example, if affected pine trees are located within the riparian zone, tree mortality can directly increase the risk of windthrow into streams, resulting in LWD loading and possibly decreased bank strength and increased sediment delivery. Furthermore, if dead pine stands are salvaged, there are risks associated with conventional forest harvesting and road construction practices. Indirectly, pine mortality (with or without subsequent salvage harvesting) reduces overall evapotranspiration losses, which at the watershed-scale is likely reflected in increased annual water yield, increased groundwater levels, and possibly increased peak flows (Uunila et al. 2006).

Strategies to address the impacts of MPB are evolving, although some suggest that the best strategy for MPB sites is just to leave them alone. Active rehabilitation of streams and riparian areas affected by MPB involves two principal objectives: (1) to reduce the potential increase in the amount and rate of runoff generated by the watershed; and (2) to ensure that the drainage network (including streams and stream crossings) has adequate capacity to handle potentially higher flows or water levels in the future without causing adverse effects (e.g., channel instability and increased turbidity). The increase in flows may be considerable (Uunila et al. 2006), and is a topic of active research (e.g., Luo et al. 2006).

Achieving the first objective involves the acceleration of hydrologic recovery through stand rehabilitation, but only where this is justified (Burton 2006). This likely would include conventional planting strategies, but attempts should be made to minimize impacts on (live) understorey vegetation and to encourage the establishment of rapidly growing pioneer species (e.g., cottonwood). Achieving the second objective involves the identification of areas and (or) sites that are sensitive to increased streamflows or groundwater levels, followed by the development of specific strategies to pre-emptively address any issues that could arise. This may include upgrading stream crossings and ditches, stabilizing vulnerable streambanks, or selectively removing dead trees and (or) LWD. Although many of these strategies have been used successfully over the years, it may take time to determine how effective these measures are in MPB-affected watersheds, as the full hydrologic impacts of MPB have yet to be observed in much of British Columbia.

Long-term Site Nutrient Balances

Working with nature to rehabilitate areas in which undesirable conditions have been created can be more successful and cost-effective than engineering approaches that work against natural processes. The restoration of long-term site nutrient balance focusses on re-establishing patterns of ecological succession. This involves establishing physical ecosystem conditions that facilitate succession (creating an appropriate "ecological stage" using the metaphor of ecological theatre[10]; Figure 18.56). Unless the species to be established match the physical and chemical conditions present, the establishment efforts may fail.

One of several conditions that must be met for the successful re-establishment of succession is the availability of soil resources—moisture, soil aeration, and nutrients. The first two components are a function of topography, slope hydrology, and soil texture and architecture, some of which may have been degraded, although some of these are a relatively fixed site feature. The third component, the soil nutrient legacy and its pattern of change over time, can be the most affected by ecosystem disturbance; therefore, the nutrient requirements of the successional stages to be established require consideration. If nutritional reserves are thought to be inadequate for the species being established, then some management actions (e.g., fertilization, organic matter amendments, or a change in species) may be needed.

One of the challenges of site nutritional assessment is the dynamic nature of nutrient availability. The relatively short "assart period" of increased nutrient availability following disturbance can mask long-term biogeochemical issues related to significant disturbance-induced losses of nutrient legacies. These legacies are important for ecosystem productivity and for the success of seral vegetation in providing slope stability and the re-establishment of hydrological function. Young trees have relatively high requirements for nutrient uptake. Once trees have accumulated sufficient nutrients to support the leaf biomass and to provide the nutritional requirements for foliage and fine root replacement through internal nutrient recycling, the tree population or community can prosper with reduced levels of soil nutrient availability. If the assart period ends before this critical accumulation of nutrients is reached, then tree growth, foliage production, and litter fall will decline and the desired plant community function may not be achieved.

Fortunately, many early-seral tree species have adaptations that help maintain the supply of soil nitrogen, the nutrient normally most depleted following erosion and other forms of soil disturbance. Alders, and to a lesser extent cottonwoods and some early-seral conifers, have nitrogen-fixation adaptations that increase the availability of nitrogen, acidify the soil, and thereby accelerate mineral weathering. This, in turn, increases the availability of other nutrients.

Qualitative assessments of long-term site nutri-

10 For an elaboration of this conceptual approach, see Kimmins 2005, 2007.

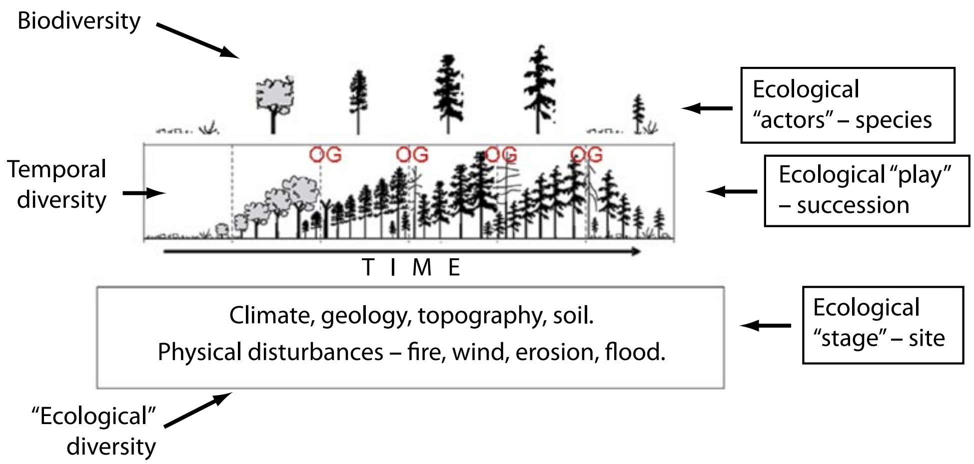

FIGURE 18.56 *Diagrammatic representation of the concept of "ecological theatre." Only one or a few plant species ("actors") are shown for each "act" (seral stage and its biotic community) of the ecological "play" (the successional sequence of communities/seral stages), whereas in reality many species ("actors") are "on stage" in each "act." This diagram implies that the "script" or "storyline" for the "ecological play" is constant and will be repeated exactly following ecosystem disturbance. In reality, it can vary according to different types, severities, spatial scales and timing of disturbances, differences in ecosystem character and condition, differences in the availability of species to colonize the area, and the resultant variation in the processes of ecosystem development. For watershed restoration efforts to be successful using natural process–based approaches, species must be closely matched to the present physical and chemical conditions and ecosystem processes (after Kimmins 2007). Note that the ecosystem condition "old growth" can occur as each seral stage evolves into the next—not only as ancient, late successional, or climax communities. (Kimmins 2007, after Kimmins 2005)*

ent balance can be undertaken by a soil scientist or ecosystem ecologist. When a quantitative assessment of long-term nutritional inventories and dynamics is deemed critical to the success of restoration efforts, ecosystem management models can be used that incorporate biogeochemical processes and tree species nutritional requirements (see Figure 18.57; www.forestry.ubc.ca/ecomodels/; Kimmins et al. 1999).

Liability

Another emerging topic related to watershed restoration is the need to better specify design criteria for restoration projects (Slate et al. 2007) and to determine liability associated with such projects. Table 18.5 shows the probability of exceeding design criteria as a function of project lifespan. Many restoration (or compensation) projects require considerable investment of time and resources. Therefore, a need exists to better define the expected lifespan of the restoration measures, the acceptable risk of failure, and the liability that will accrue to the proponent / design team if project objectives are not achieved because of unforeseen events.

By way of example, while floating down a placid stream, a child drowned after becoming entangled in an instream LWD structure. Who accepts responsibility for this tragedy and what qualifications and (or) insurance should the designer or sponsoring agency be expected to possess? These issues can significantly affect who undertakes restoration projects and the liability that is assumed.

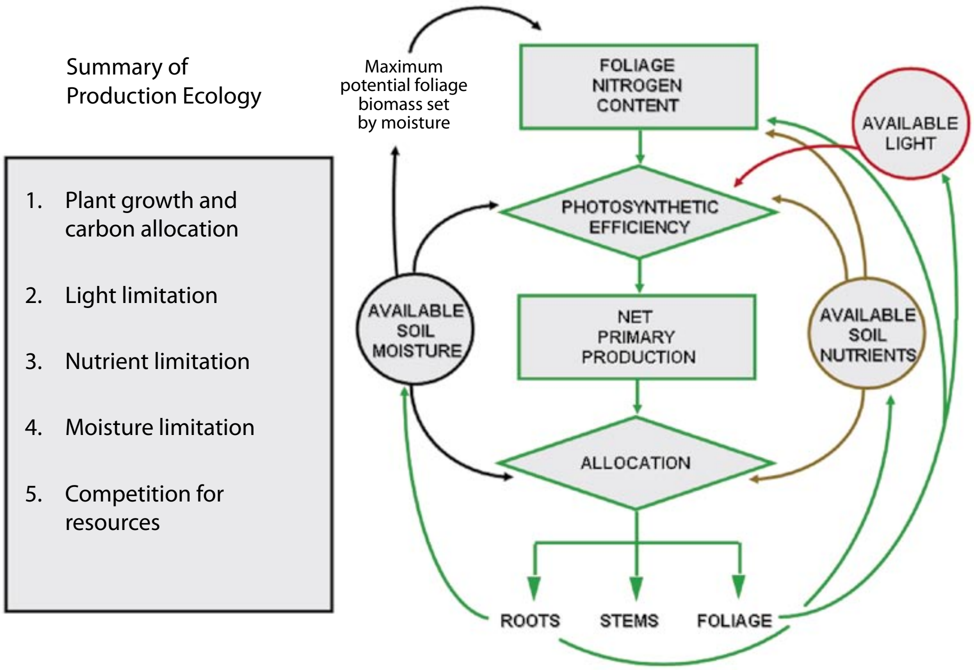

FIGURE 18.57 *The major elements of production ecology. These elements should be incorporated into assessments of potential biogeochemical limitations on the success of restoration activities. The competition for resources includes herbs and shrubs, as well as all the tree species present. The FORECAST ecosystem management model is one decision-support tool used for this purpose (Kimmins et al. 1999; Seely et al. 1999, 2004). (Modified from Kimmins 1993)*

TABLE 18.5 *Probability of exceeding design criteria (%) as a function of project lifespan. (Table prepared by M. Miles and Associates Ltd. using a formula in Kite 1976)*

Average return period (years)	**Anticipated project lifespan (years)**																
	2	**5**	**8**	**10**	**15**	**20**	**25**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**150**	**200**
2	75	97	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
5	36	67	83	89	96	99	100	100	100	100	100	100	100	100	100	100	100
10	19	41	57	65	79	88	93	96	99	99	100	100	100	100	100	100	100
20	10	23	34	40	54	64	72	79	87	92	95	97	98	99	99	100	100
25	8	18	28	34	46	56	64	71	80	87	91	94	96	97	98	100	100
30	7	16	24	29	40	49	57	64	74	82	87	91	93	95	97	99	100
40	5	12	18	22	32	40	47	53	64	72	78	83	87	90	92	98	99
50	4	10	15	18	26	33	40	45	55	64	70	76	80	84	87	95	98
60	3	8	13	15	22	29	34	40	49	57	64	69	74	78	81	92	97
100	2	5	8	10	14	18	22	26	33	39	45	51	55	60	63	78	87
200	1	2	4	5	7	10	12	14	18	22	26	30	33	36	39	53	63
500	0.4	1	1.6	2	3	4	5	6	8	10	11	13	15	16	18	26	33
1000	0.2	0.5	0.8	1	1.5	2	2	3	4	5	6	7	8	9	10	14	18
1500	0.1	0.3	0.5	0.7	1	1.3	1.7	2	3	3	4	5	5	6	6	10	12
2000	0.1	0.2	0.4	0.5	0.7	1	1.2	1.5	2	2	3	3	4	4	5	7	10

Design Methodology

Restoration is an emerging science; consequently, the most appropriate techniques for accomplishing desired objectives are the subject of many active debates. The difference in opinion among practitioners over the importance and role of red alder in restoration is discussed above; however, the combined approach of both "sides" can provide very effective treatments. For instance, the Aquatic Conservation Strategy of the Northwest Forest Plan, as applied in the U.S. Pacific Northwest by federal land management agencies, provides an example of an integrated, whole-watershed approach in which multiple goals are achieved by using a variety of treatments (Reeves et al. 2006).

As this chapter indicates, stream restoration methodologies are becoming increasingly sophisticated, and the engineering profession is beginning to see this type of work as within their regulated scope of practice. Some conflicts may be unavoidable, given that stream restoration work is currently designed mainly by community "stream keepers"—environmentally concerned citizens or biologists who have varying levels of "classic engineering" training. This disparity in background and outlook also applies at the professional level. For example a well-known stream classification system (Rosgen 1996) is commonly employed to define "reference reaches" and identify suitable restoration strategies (see Rosgen and Fittante 1986). In contrast, many fluvial geomorphologists and river engineers base their analyses on hydraulic geometry relationships, hydraulic and sediment transport calculations, and numerical models (e.g., Kondolf 1995; Ashmore 1999; Walker et al. 2005). Again, this particular disparity in approach is actively being debated.

The liability issues described previously may inevitably lead to increasingly sophisticated design procedures and an evolution in both the methods by which these are derived and the qualifications of the people who prepare them. In addition, increasing demands by regulatory agencies (e.g., Fisheries and Oceans Canada, Transport Canada [i.e. *Navigable Waters Protection Act*], B.C. Ministry of Environment, B.C. Ministry of Forests and Range) and standards set by these agencies will lead to an increased sophistication of design. In the future, ensuring that this transition is achieved in an amenable manner will likely require considerable effort.

SUMMARY

In British Columbia over the last 20–25 years, and especially since 1993, substantial experience has been gained in physical watershed assessments and rehabilitation treatments to address impacts from historic forest development. The success of restoration projects depends on setting clear goals for the project and specific objectives for individual remedial measures. It is critical to understand the physical and ecological processes at work in the watershed and to work with these processes in designing and implementing restoration measures.

Some measures, such as reducing sediment sources to streams by deactivating roads on steep slopes, have achieved considerable success in the short term. Other rehabilitation measures, such as promoting conversion to conifers in disturbance-generated alder riparian forests, will take many years to realize the full benefits. Perhaps the most daunting challenge involves the destabilization of large alluvial streams by riparian logging and other development. Decades later, little recovery is evident in some of these streams, and no short-term solutions are available to achieve floodplain stability.

As with many fields of developing science, there are divergent views on restoration approaches and treatment methodologies. For this reason, it is essential to set specific objectives and select the approach most likely to achieve those objectives and the overarching restoration goal. The type of treatment selected may also depend on other factors, such as legislated requirements for site remediation or reforestation and the expected time frames for different approaches to achieve the desired results.

An important consideration in restoration planning is the availability of future funding for measures that require ongoing maintenance or retreatment to meet project objectives. The availability of long-term funding for monitoring rehabilitation treatments may be uncertain, yet monitoring needs to critically evaluate performance. As well as confirming successful strategies, monitoring identifies cases where treatments did not work, either through a loss of integrity of the measures or through a failure to achieve the desired results. Lessons learned from these cases will inform future restoration actions. Forest development (as well as many other activities) continues in many watersheds in which restoration projects were undertaken. An important goal for current forest management is to manage ongoing development in a manner that allows for continued recovery from past impacts.

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Climate Change Effects on Watershed Processes in British Columbia

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INTRODUCTION

A changing climate in British Columbia is expected to have many important effects on watershed processes that in turn will affect values such as water quality, water supplies, slope stability, and terrestrial and aquatic habitats. In many parts of British Columbia, the effects of too much or too little water have already been observed and it is possible that an increased probability of droughts, floods, and landslides will result in considerable socio-economic, biological, and (or) physical changes in the future (Spittlehouse and Stewart 2004; Walker and Sydneysmith 2007). The influence of climate change on watershed processes is critically important to understand and to manage for now and in the future, as these functions directly determine human well-being in terms of public health, the economy, communities, and cultures.

In this chapter, we provide a summary of research detailing recent climate changes in British Columbia and possible future climate scenarios. We then discuss how watershed processes may be affected by climate change, and the implications of these changes to hydrology, geomorphology, and aquatic ecology in British Columbia. We conclude with a discussion of requirements for incorporating climate change–affected watershed processes into hydrologic models used at the forest management scale.

This chapter does not provide an overview of the causes of climate change, global climate model projections, downscaling models, or the key issues surrounding them. Further information on these topics can be found in Barrow et al. (editors, 2004), Intergovernmental Panel on Climate Change (2007), Parry et al. (editors, 2007), Parson et al. (2007), Randall et al. (2007), and Solomon et al. (editors, 2007). For material specific to British Columbia, the reader is referred to Rodenhuis et al. (2007), Spittlehouse (2008), and Chapter 3 (“Weather and Climate”).

Historical Trends in Air Temperature and Precipitation

Historical trends[1] in air temperature and precipitation provide important context against which future climate projections may be evaluated. Trend results, however, vary with the time period of analysis (i.e., 30, 50, 100 years), and in particular with the starting point of any trend calculation. Climate variability from atmosphere-ocean oscillations, such as El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Arctic Oscillation (AO), and Pacific North American Pattern (PNA), can also complicate historical trends, and may amplify responses (Gershunov and Barnett 1998; Storlazzi et al. 2000) or cause changes of the same or greater magnitude than those in historical, long-term trends (Rodenhuis et al. 2007). For example, the 100-year trend analysis conducted over British Columbia is sensitive to the early 1920s drought period that occurred during a warm-PDO phase (Zhang et al. 2000). Further discussion of the influence of sea surface temperatures and large-scale atmospheric circulation patterns on British Columbia's climate can be found in Chapter 3 ("Weather and Climate").

Analyses of historical climate records for British Columbia show a rise in annual air temperatures, with the greatest warming occurring in the winter (Rodenhuis et al. 2007). Across the province, warming has been greater in the north than in the southern and coastal regions (Table 19.1; Figure 19.1). For example, temperature trends from 1971 to 2004 (updated from Rodenhuis et al. 2007) show increased annual mean temperatures and increased winter mean temperatures over British Columbia (Table 19.1). Nighttime temperatures have increased more than daytime temperatures (Vincent and Mekis 2006). This change may be associated with an increase in high clouds[2] occurring at nighttime and a decrease in low–middle cloudiness that might have contributed to the warming of daily minimum and maximum temperatures (Milewska 2008). The changes in temperatures over the past 50 years also have been linked to increased atmospheric water vapour and associated dew point and specific humidity trends during the winter and spring (Vincent et al. 2007).

Changes in daily extreme temperatures have also been observed in Canada. A global study found significant decreases in the number of days with extreme low daily temperatures, while increases in the number of extreme warm days were not significant over the 20th century (Easterling et al. 2000). In Canada, Bonsal et al. (2001) investigated seasonal extremes in southern Canada from 1900 to 1998. These authors found that fewer extreme low-temperature days occurred during winter, spring, and summer, and that the number of extreme hot days did not change from 1900 to 1998 (Bonsal et al. 2001). Some of these changes are related not only to climate change, but also to climate variability, such as ENSO (Bonsal et al. 2001). The warm (cold) phase of ENSO was associated with a significant increase (decrease) in the occurrence of warm (cold) spells and the number of extreme warm (cold) days across most of Canada over the 1950–1998 period (Shabbar and Bonsal 2004).

Trends in annual precipitation across British Columbia for the 100-, 50-, and 30-year periods are variable both spatially and through trend periods, as compared to temperature trends (Table 19.1; Figure 19.2). In general, average annual precipitation has increased (1.4 mm/month per decade) over the past 100 years (Table 19.1), with larger percentage increases occurring in regions with comparatively lower annual precipitation (Rodenhuis et al. 2007). Precipitation indices compiled for Canada over the 20th century illustrate an increase in annual snowfall from 1900 to 1970, followed by a considerable decrease until the early 1980s (Vincent and Mekis 2006). Generally, precipitation over the past 50 years has decreased over the southern portion of the province, most notably in the south coastal region, the Columbia River basin, and in the Peace watershed regions during winter. Conversely, precipitation has increased in spring, particularly in the southern regions (Rodenhuis et al. 2007).

Climate oscillations play a role in the above-mentioned precipitation trends, as presented and discussed in Chapter 3 ("Weather and Climate"). The

1 Paleoclimatic trends in precipitation and temperature are not considered in this chapter.
2 Clouds with a base height of 6–12 km above the Earth's surface, referred to as cirrus, cirrocumulus, or cirrostratus clouds.

TABLE 19.1 *Historical trends in 30-, 50-, and 100-year periods (1971–2004, 1951–2004, and 1901–2004, respectively). Temperatures and precipitation trends calculated from mean daily values as seasonal (winter as December–February and summer as June–August) and annual averages. Values provided for the province as a whole, and for the Coastal, South, North, and Georgia Basin regions (see Figure 19.1).*

Season	Time period (years)	British Columbia	South	North	Coastal	Georgia Basin
Temperature (°C per decade)						
Winter	30	0.77	0.77	0.90	0.60	0.44
	50	0.45	0.38	0.59	0.35	0.22
	100	0.22	0.22	0.25	0.18	0.15
Summer	30	0.33	0.28	0.32	0.40	0.52
	50	0.18	0.21	0.14	0.19	0.30
	100	0.07	0.08	0.07	0.05	0.06
Annual	30	0.41	0.41	0.41	0.42	0.45
	50	0.25	0.25	0.27	0.22	0.22
	100	0.12	0.12	0.13	0.10	0.11
Precipitation (mm/month per decade)						
Winter	30	–4.28	–4.90	–2.47	–6.08	–8.06
	50	–1.90	–2.44	–0.55	–3.06	–5.35
	100	1.77	1.26	1.19	3.39	1.78
Summer	30	1.41	1.83	0.05	3.50	–1.80
	50	1.31	1.28	0.97	2.11	–0.27
	100	1.18	1.37	1.21	0.91	0.93
Annual	30	0.75	1.06	0.07	1.63	–0.42
	50	0.67	0.86	0.41	1.01	–0.43
	100	1.41	1.22	1.06	2.25	1.20

impact of the 1976 positive PDO phase shift has been well documented in British Columbia and the Pacific Northwest (i.e., reduction in snowpack: Moore and McKendry 1996; fisheries effects: Mantua et al. 1997). The recent 30-year trend period (1971–2004) falls almost entirely within this positive phase of the PDO. The positive phase of the PDO in British Columbia has been noted to cause warming throughout western Canada and decreased precipitation in the mountainous and interior regions of the province (Stahl et al. 2006).

Trends in extreme events for the past 50 years indicate that seasonal patterns of precipitation in western Canada are changing. In the Pacific Northwest, recent shifts in the occurrence and magnitude of extreme rainfall intensities have been observed, with storms becoming more frequent and of a greater magnitude for a given frequency. Madsen and Figdor (2007) observed an 18% increase in extreme precipitation events over the 1948–2006 period. Similarly, Rosenberg et al. (2009) observed significant increases in extreme precipitation events in the Puget Sound, with increases up to 37% from the 1956–1980 period to the 1981–2005 period. These increases represented a shift in which the 50-year storm event became an 8.4-year storm event. Stone et al. (2000) found a significant increase in heavy rainfall events during May, June, and July from 1950 to 1995. Zhang et al. (2000) examined the differences between the first and the second half of the century and found an increase in both extreme wet and extreme dry conditions in summer (1950–1998). Although the national trend shows that only the number of days with heavy precipitation increased significantly over the past 50 years, some stations in southern British Columbia show significant increases in two extreme indices: (1) the highest 5-day precipitation, and (2) very wet days (the number of days with precipitation ≥ 95th percentile) (Vincent and Mekis 2006).

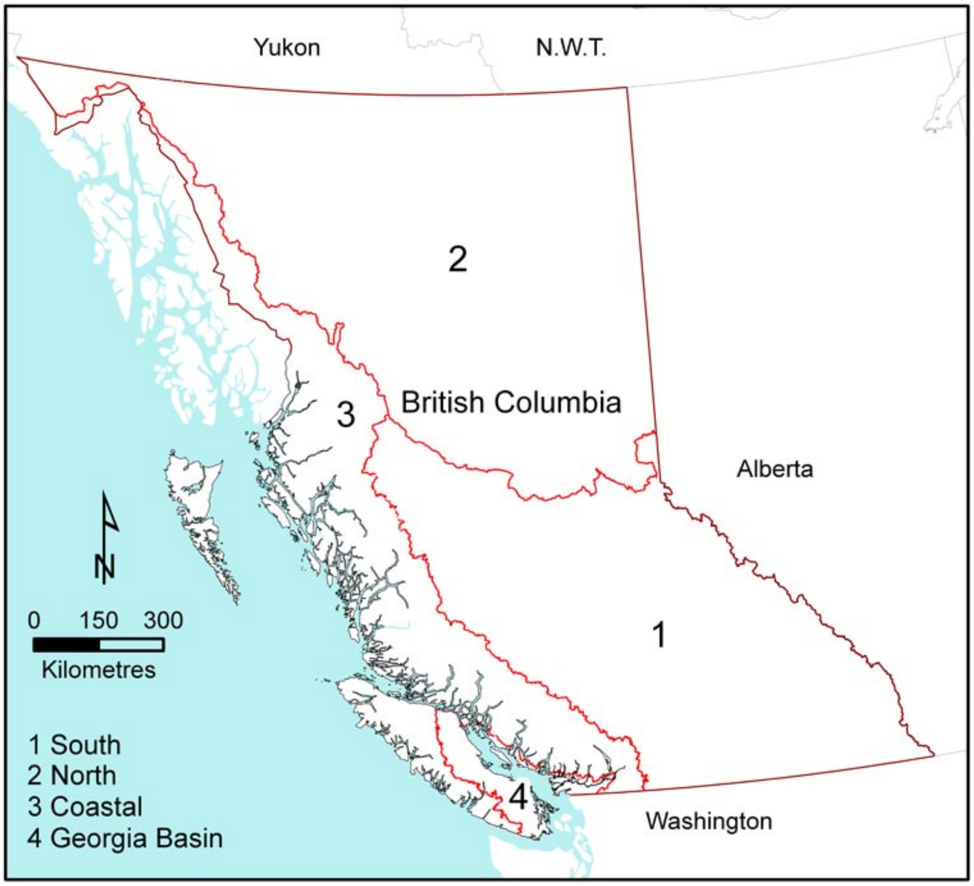


FIGURE 19.1 *Map of British Columbia regions used in Table 19.1.*

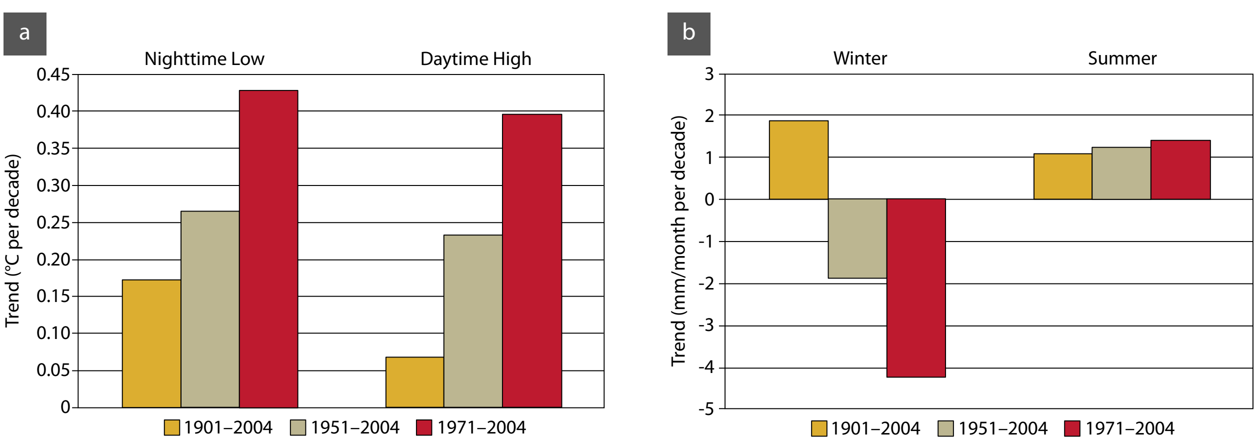


FIGURE 19.2 *Mean of all trends across British Columbia for (a) minimum temperature (nighttime low) and maximum temperature (daytime high), and (b) precipitation based on CANGRID[3] gridded time series of historical climate. (Data from Environment Canada)*

3 CANGRID is a gridded 50 km² product developed by Environment Canada, based on Adjusted Historical Canadian Climate Data (AHCCD).

Historical Trends in Snow, Seasonal Ice Cover, Permafrost, and Glaciers

The interactions between increased temperature and shifts in precipitation form (i.e., snow to rain) in British Columbia are complex and not fully understood. Research in the western United States suggests that the snow-to-rain ratio is changing and less snow is falling during winter at lower elevations on the west coast of the United States (Knowles et al. 2006). Mote et al. (2005) reported a general decline in snowpacks over much of western North America from 1950 to 1997, despite increases in precipitation. Between the mid-1980s and 2008, McCabe and Wolock (2009) reported above-average winter temperatures and below average snow water equivalent (SWE) in the western United States. In British Columbia, the Ministry of Environment reported overall decreasing trends in April 1st SWE from 1956 to 2005 based on data from 73 long-term snow courses (63 decreased, 10 increased). The largest decreases occurred in the mid-Fraser Basin, whereas the Peace, Skeena, and Nechako Basins had no notable change over the 50-year study period, and overall the provincial average SWE decreased 18% (B.C. Ministry of Environment 2007).

Increasing temperatures have also affected the length and date of seasonal lake ice cover. A Canada-wide study showed significantly earlier lake "ice-free" dates for the 1951–2000 period (Duguay et al. 2006). In several British Columbia lakes, the first melt date and ice-free date decreased by 2–8 days per decade from 1945 to 1993, whereas the duration of ice cover decreased by up to 48 days over the 1976–2005 period (B.C. Ministry of Environment 2002; Rodenhuis et al. 2007).

Permafrost in Canada is also changing. In British Columbia, sporadic discontinuous permafrost exists in the northern latitudes, whereas isolated patches of permafrost exist south of Prince Rupert and Fort St. John and at higher elevations to the United States border through the Coast and Rocky Mountain ranges. Recent analysis has shown that permafrost in many regions of North America is warming (Brown et al. 2004). In looking at recent trends from the Canadian Permafrost Thermal Monitoring Network, Smith et al. (2005) reported that while the timing and magnitude of warming varied regionally, warming trends in permafrost were largely consistent with air temperature trends observed since the 1970s. In their analysis, Smith et al. (2005) noted that local conditions importantly influenced the response of the permafrost thermal regime.

Glaciers in British Columbia are also out of equilibrium with the current climate and are adjusting to changes in seasonal precipitation and elevated temperatures, with widespread glacial volume loss and retreat in most regions. For example, the Illecillewaet Glacier in Glacier National Park has receded over 1 km since measurements began in the 1880s (Parks Canada 2005). In general, glaciers have been retreating since the end of the Little Ice Age (mid-19th century), although some glaciers have exhibited periods of stability at the terminus and even advances (Moore et al. 2009). For example, Moore et al. (2009) reported that the terminus of Illecillewaet Glacier remained stationary from 1960 until 1972, and then advanced until 1990. It has subsequently resumed its retreat. This behaviour is consistent with the decadal time scale of glacier terminus response to climate variability (Oerlemans 2001). Schiefer et al. (2007) reported that the recent rate of glacier loss in the Coast Mountains is approximately double that observed for the previous two decades. A compilation of glacier area changes in the period 1985–2005 indicates glacier retreat in all regions of the province (Bolch et al. 2010), with an 11% loss in total glacier area over this period. On Vancouver Island, the central Coast Mountains, and the northern Interior ranges, ice-covered areas have declined by more than 20% over this period (Bolch et al. 2010).

The dominant trend of glacier retreat has influenced streamflow volumes, leading to declines in late-summer streamflow (Moore et al. 2009). However, Moore et al. (2009) also noted that some exceptions exist, particularly in glacier-fed watersheds in northwest British Columbia and the Yukon that experienced increased flows over recent decades (due to ice melt), consistent with the findings of Fleming and Clarke (2003). This is a function of the glacier-covered area in a catchment; runoff per unit area from glaciers is higher as glaciers retreat, but the total glacier contribution to a basin declines with reductions in glacier area. This is discussed further in "Glacier Mass Balance Adjustments and Streamflow Response," below.

Historical Trends in Landslides and Other Geomorphic Processes

In British Columbia, much of the contemporary landscape has been shaped by previous glacial periods (see Chapter 2, "Physiography of British Columbia"). Persistent paraglacial effects exist in British Columbia whereby secondary remobilization of Quaternary sediments has led to a relationship of increasing contemporary sediment yield (sediment yield per unit area) with increasing drainage area (Church and Slaymaker 1989). This suggests that, at a landscape level, British Columbia is still responding to the last Cordilleran glaciation.

Alpine glacial retreat has led to a variety of geomorphic processes in periglacial (proximal to glaciers) and alpine environments (O'Connor and Costa 1993; Evans and Clague 1997; Ryder 1998; Moore et al. 2009). For example, debuttressing of support to lateral slopes caused by glacial retreat has led to deep-seated rock failures in some areas (Holm et al. 2004). Flooding attributed to the failure of moraine-dammed lakes impounded by Little Ice Age deposits has also been observed throughout the Coast Mountains (McKillop and Clague 2007). Glacial lake outburst floods (jökulhaups) have occurred in areas of the province, predominantly along the British Columbia–Alaska border and in the southwest Coast Mountains (Clague and Evans 1997; Geertsema 2000). Though the relationship to climate variability and change in the region is not completely understood, in recently exposed glacial forefield areas, sediment production rates have increased from both primary erosion of exposed slopes and remobilization of stored channel deposits (Orwin and Smart 2004; Schiefer and Gilbert 2007).

Landslides in British Columbia are often triggered by major storm events (see Chapter 8, "Hillslope Processes," and Chapter 9, "Forest Management Effects on Hillslope Processes"). Septer and Schwab (1995) summarized extreme rainstorm and landslide events in northwest British Columbia over the 1981–1991 period. Guthrie and Brown (2008) estimated the variability in landslide rates over the Holocene and suggested that increases in landslide rates doubled during shifts from drier to wetter periods. Shifts in landslide rates attributed to changes in climatic regimes are thought to be of a similar order of magnitude or smaller when compared to landslide responses to forest management in the 20th century (Campbell and Church 2003; Guthrie and Brown 2008).

In northern British Columbia, shallow slides and debris flows have occurred during infrequent large storms. Egginton et al. (2007) noted that large cyclonic storms and convective thunderstorms have triggered recent landslides in the north, but large slides (greater than 0.5 Mm^3) are more typically preceded by long periods of wetter or warmer climate. Large rock slides appear to have responded to warming trends of the past few decades by destabilizing from snow and ice melt and increasing freeze thaw processes (Egginton 2005; Geertsema et al. 2007). Larger soil slides are more common during long periods (years to decades) of above-average precipitation, likely from soil saturation (Egginton 2005; Geertsema et al. 2007). Prolonged periods of increased precipitation or temperature have increased the vulnerability of slopes to failure in these areas, whereas large or intense storms are often the trigger. All of these conditions are expected to be further enhanced under current climate change scenarios.

Historical Trends in Groundwater Levels

Spatial and temporal variations in groundwater levels are caused by both human and natural factors. Human factors often involve groundwater extraction (e.g., pumping and irrigation) or land use change (urbanization or deforestation). Natural factors may include the effects of tides on coastal aquifers, the influence of seasonal variations in precipitation and recharge, and the effects of longer-duration climatic cycles. Historical time series of groundwater levels (groundwater hydrographs) often illustrate cyclic behaviour ranging from short term (i.e., hours, days) to long term (i.e., years, decades). Long-term monitoring of groundwater levels is therefore necessary to quantify groundwater trends and discern the effects of climatic changes on groundwater hydrology. (A brief introduction to groundwater hydrology is provided in Chapter 6, "Hydrologic Processes and Watershed Response").

Across British Columbia, groundwater levels and quality are monitored in 145 observation wells (as of July 2009).[4] These observation wells are located primarily in developed aquifers to examine the effects of water extraction and development on groundwater availability and quality. Unfortunately, because of a short data record, and location in areas influenced by human activity, many of the wells are likely unsuitable for climate change detection purposes.[5] Furthermore, British Columbia contains a wide range of

4 For details about the observation well network, go to: www.env.gov.bc.ca/wsd/data_searches/obswell/index.html.
5 Moore, R.D., D.M. Allen, and K. Stahl 2007. Climate change and low flows: influences of groundwater and glaciers. Nat. Resour. Can., Can. Climate Action Fund, Ottawa, Ont. Can. Climate Action Fund Proj. No. A875. Unpubl. report.

aquifer types (Wei et al. 2009) with varying physical properties that have a strong control on groundwater response to climatic changes.

Most recently, declining groundwater levels trends have been reported at 35% of the provincial observation wells for the 2000–2005 period (B.C. Ministry of Environment 2007). This represents a percentage increase in the rate of decline compared to groundwater level declines reported for only 14% of wells for the 1995–2000 period. The greater decline was attributed to human activities rather than climate causes, as the majority of monitoring wells showing declines were located in regions with intense urban development and groundwater use (i.e., Vancouver Island, Gulf Islands, and the Okanagan Valley). Unravelling such complexity of causal factors is confounded by climate variability; however, analysis of groundwater hydrographs in combination with climate and streamflow data offers some insight. Fleming and Quilty (2006) investigated groundwater and stream hydrographs for a small area of the lower Fraser Valley (four observation wells) and found that groundwater levels tend to be higher during La Niña years and lower during El Niño years because of the associated variations in precipitation and recharge. These results also indicate that groundwater levels can lag in response to climate variation. Moore et al.[6] examined a larger subsample of the provincial well-monitoring database and correlated groundwater levels with nearby streamflow and precipitation records over a 20–30 year period. Their results indicate that groundwater levels have decreased over the areas examined, whereas winter precipitation and recharge increased over the same time period. The results are highly variable, however, and likely related to differences in aquifer properties, surface water–groundwater interactions, and the effects of water withdrawals.[7]

Historical Trends in Streamflow

Province-wide studies examining historical (undisturbed) streamflow patterns are not generally available. This is likely related to the limited availability of long-term hydrologic records and the large variability in hydrologic regimes occurring across British Columbia. An important component of diagnosing the changes in streamflow is the isolation of natural and human-caused disturbance effects (e.g., forest harvesting) from those effects attributed to climate changes and variability. In many areas in British Columbia, this is a challenge because of the predominance of watershed disturbances.

Several studies have documented streamflow trends for provincial watersheds. Important documented changes include observations of earlier spring peak freshets and prolonged, dry late-summer periods for streams in south-central British Columbia (Leith and Whitfield 1998; Whitfield and Cannon 2000). These changes are attributed to a greater percentage of rain falling versus accumulating as snow, although this hypothesis was only recently verified using standard statistical approaches (P. Whitfield, Environmental Studies, Meteorological Service of Canada, pers. comm., 2007). One recent study using trends in sequential 5-day periods observed that rising air temperatures in December and early January led to decreased snowpack, increased runoff from fall to early winter, and decreased flows from May through August (1976–2006) in the Little Swift River Basin, near Barkerville (Déry et al. 2009).

In a Canada-wide survey, Zhang et al. (2001) documented declining trends in annual mean streamflow for the past 30–50 years (three time periods: 1967–1996, 1957–1996, and 1947–1996); however, these results were variable across seasons, with an increase in mean monthly streamflow across Canada in March and April, and decreases in summer and fall. For many of the variables studied, Zhang et al. (2001) identified southern British Columbia as a significantly affected region. Several important streamflow metrics, including the date of spring high-flow season, annual maximum daily mean streamflow, centroid (date) of annual streamflow, and spring ice break-up, occurred earlier in the season (Zhang et al. 2001).

Advances of 10–30 days in the centre of mass of annual streamflow (i.e., the date by which half of the annual total streamflow runoff has occurred) have been measured in streams in Pacific North America from 1948 to 2002 (Stewart et al. 2005). Other analyses of changes in the date of the centre of volume (a similar metric), gave varying results when computed for the calendar year and hydrologic year (Déry et al. 2009). These varying results illustrate that analyses can be strongly affected by the date metrics used to identify trends in streamflow.

6 Ibid.
7 Ibid.

The magnitude and direction of the changes to streamflow vary across British Columbia depending on the time period of analysis and the hydro-climatic region. For example, Rodenhuis et al. (2007) reported differing trends in mean annual streamflow for British Columbia than those reported by Zhang et al. (2001). Rodenhuis et al. (2007) attributed these differences to the different PDO phases that occurred during their analysis period (1976–2005) compared to the 1967–1996 period used by Zhang et al. (2001).

Analyses conducted for this chapter at several stations (Table 19.2) representative of different regions in British Columbia (updated from Rodenhuis et al. 2007) indicate that the largest amount of change appears to be occurring in coastal watersheds. Regimes are shifting towards increased winter rainfall, and declining snow accumulation, with subsequent changes in the timing and amount of runoff (i.e., weakened snowmelt component). This, coupled with decreased summer precipitation, is shifting the streamflow pattern in coastal watersheds. In other systems throughout British Columbia, increasing temperatures over the past 15 years and changing precipitation patterns have altered the magnitude and timing of snowpack and spring melt. In the Okanagan region, for example, changes in snowpack accumulation are resulting in an earlier spring peak streamflow and leading to declining maximum flows and extended minimum flows in late summer and early fall. The Fraser and Columbia River nival-glacial systems show increased peak flows and lower recessional flows, illustrating changes in the associated watersheds, perhaps away from a glacier-dominated regime towards a snow-dominated regime with an earlier freshet and faster recessional period.

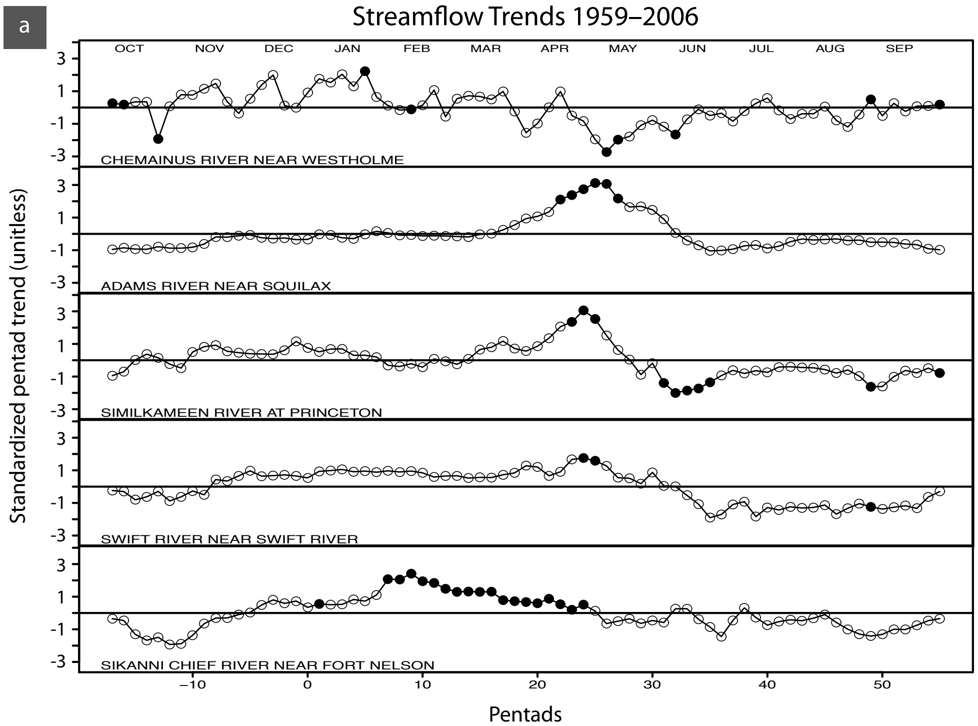
Trend analysis of sequential 5-day average runoff values was conducted at a collection of stations representative of several hydro-climatic regimes in British Columbia (Table 19.2). Two periods were investigated: (1) 1959–2006 (48 years, Figure 19.3a), and (2) 1973–2006 (34 years, Figure 19.3b). Analysis results for the longer record (1959–2006; Figure 19.3a) show that the nival-supported pluvial Chemainus River in British Columbia's coastal region had a varied response over the record, with predominantly increased flow in winter and decreased flow during May. The nival–glacial Adams River had increased flow in spring and decreased flow in all other seasons. The nival/hybrid Similkameen River located in the Okanagan and the nival Swift River in the northwest had increased winter and spring flows and decreased summer flow. In the Peace region, the nival Sikanni Chief had increased flow in December through April and decreases in May through November.

For the more recent years of record (1973–2006; Figure 19.3b) the above-mentioned stations and one additional record for Fry Creek, located in the Columbia River Basin, were analyzed. Fry Creek is a small, nival–glacial system that had decreases in flow in June, July, August, and September over this period, similar to the Adams River in the Interior, another glaciated system. Decreased flow in September was most prominent in the Adams. Decreases in streamflow also occurred for the nival-hybrid Similkameen River and the nival Swift River during the summer months. In these more recent years of record (1973–2006), increased streamflow was observed from November to April and decreased streamflow from June to September across all stations, with the exception of the Sikanni Chief River, which had decreases in October through December, and the Chemainus River, which had decreases in February.

The trend analysis shown here employed techniques developed by Déry et al. (2009). Déry et al. (2009) found that in the pluvial systems of the Yakoun, Zeballos, and San Juan Rivers, positive trends (increasing streamflow) were observed in winter and negative trends (decreasing streamflow) were ob-

TABLE 19.2 *Water Survey of Canada gauging station information for various streamflow regimes in British Columbia*

Name	WSC station no.	Region	Streamflow regime	Basin size (km²)	Continuous years of record	Period of record
Chemainus River	08HA001	Coastal	nival supported pluvial	355	52	1955–2006
Similkameen River	08NL007	Okanagan	nival/hybrid	1185	62	1945–2006
Adams River	08LD001	Interior	nival–glacial	3080	58	1949–2006
Fry Creek	08NH130	Columbia	nival–glacial	586	34	1973–2006
Sikanni Chief River	10CB001	Peace	nival	2160	47	1960–2006
Swift River	09AE003	Northwest	nival	3320	48	1959–2006



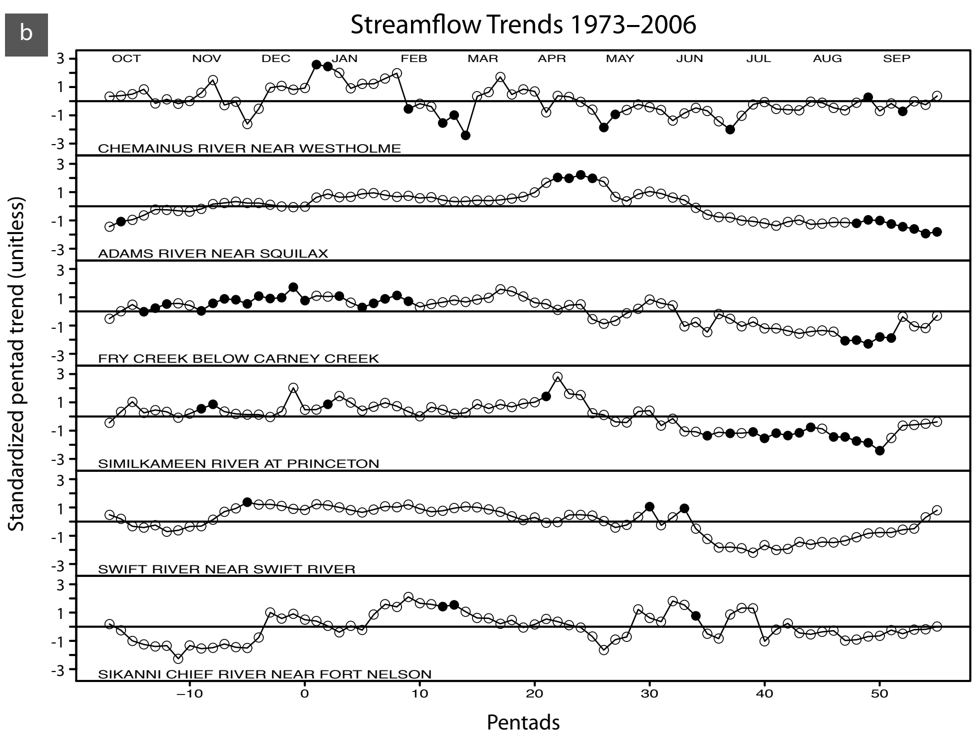


FIGURE 19.3 *(a) Streamflow sequential 5-day average runoff trends for the long-term historical period 1959–2006 for five streams located in different regimes throughout British Columbia; and (b) streamflow sequential 5-day average runoff trends for the recent historical period 1973–2006 for six streams located in different regimes throughout British Columbia (see Table 19.2 for information on gauging stations). Solid circles are significant results, open circles are non-significant results at the 95% confidence interval. Standardized results above zero indicate increased streamflow, whereas results below zero indicate decreased streamflow.*

served in summer from 1972 to 2006. The nival and glacial systems (Dore, Tuya, and Little Swift Rivers) had large positive trends (increasing streamflow) during spring followed by strong negative trends (decreasing streamflow) in summer, which suggests a phase shift towards earlier spring freshets. Surprise Creek, a nival–glacial system, showed a pronounced positive discharge trend throughout the summer, unlike many other similar rivers in western Canada (Déry et al. 2009).

Although trends illustrate how streamflow is changing over long periods, events caused by climate variability may result in short-term shifts in streamflow. (Streamflow variability is discussed in Chapter 3, "Weather and Climate.") The influence of the modes of climate variability (e.g., ENSO and PDO) on streamflow is evident and often confounds identification of historical trends. On the south Coast, some streams that are normally rainfall-dominated have snowmelt runoff in the spring during cool La Niña years (Fleming et al. 2007). This can result in years with two streamflow peaks in watersheds where normally only one would occur (e.g., Figure 19.4a, Chemainus River). During El Niño years, substantially less streamflow may occur from May to August in snowmelt-dominated basins, especially those in the Okanagan Basin (e.g., Figure 19.4b, Similkameen River; Rodenhuis et al. 2007) but may have little effect in the north of the province where ENSO signals are less pronounced (e.g., Figure 19.4c, Swift River). Warm PDO phases, such as the one that occurred from 1977 to 1998, advance the spring or summer freshet, lower peak flows, and cause drier summer periods for many streams in British Columbia (Zhang et al. 2000). Some exceptions occur in northern British Columbia where the opposite response can occur during warm PDO phases (e.g., Figure 19.4d, Sikanni Chief River; Rodenhuis et al. 2007). This is important to note because climate and streamflow responses during different climate oscillations are not necessarily uniform across regions, and often depend on (or are related to) the hydrologic regime, physiography, and climate of the region under consideration.

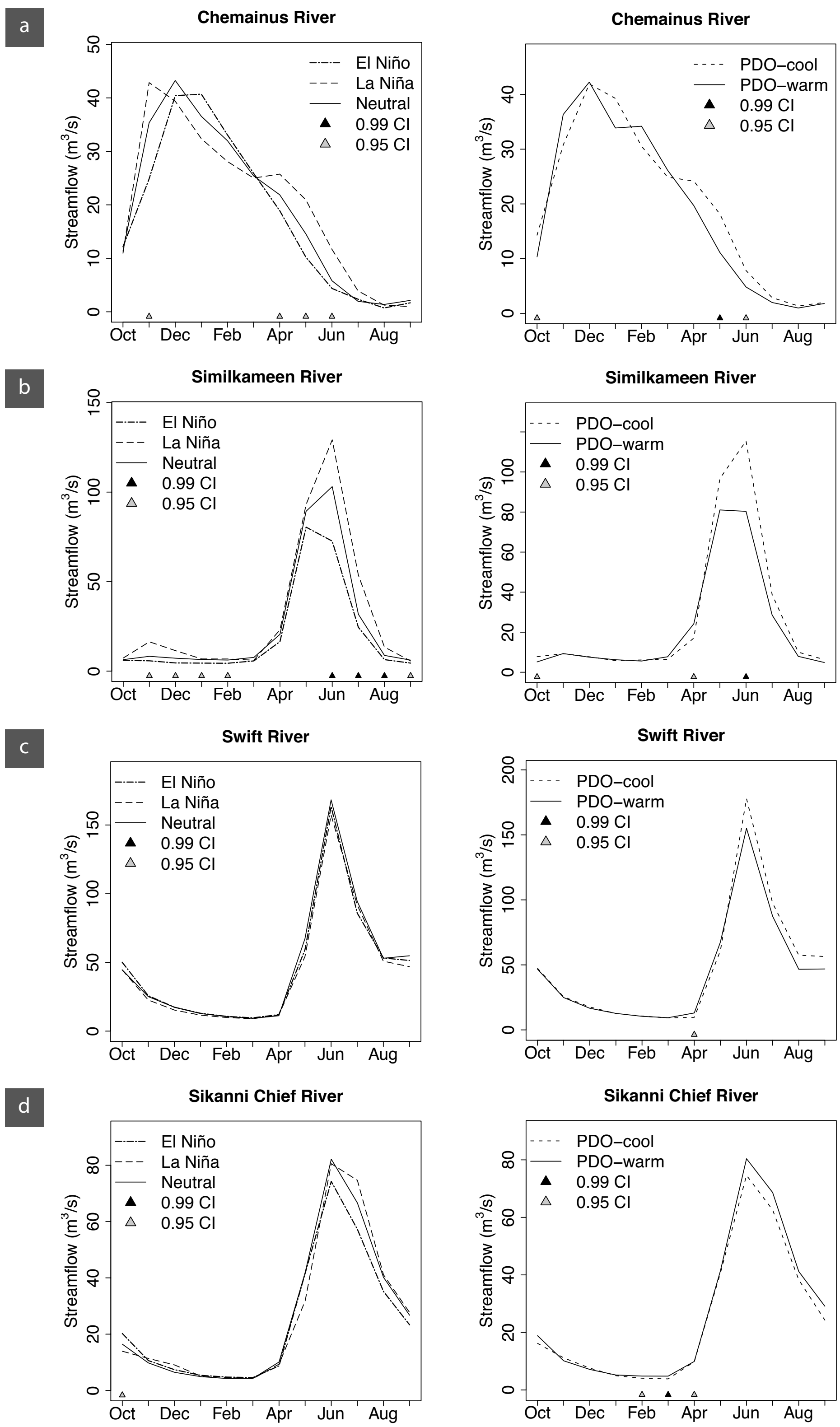


FIGURE 19.4 *Monthly average streamflow occurring during ENSO periods (left-hand plots) and PDO-cool (right-hand plots) for: (a) Chemainus River, (b) Similkameen River, (c) Swift River, and (d) Sikanni Chief River. See Table 19.2 for information on gauging stations. The grey and black triangles indicate significant differences at the 95% (0.95 CI) and 99% (0.99 CI) confidence levels, respectively.*

British Columbia Projections by Emissions Scenario

Projections of future climates are available from numerous global climate models (GCMs) and for a range of greenhouse gas emissions scenarios. These emissions scenarios[8] depend on future population, technology, economic growth, and international trade (Intergovernmental Panel on Climate Change 2007), but do not consider intentional co-operation to prevent climate change. Importantly, each GCM can project different future climates for the same emissions scenario because each models specific processes (e.g., evaporation) differently.

In general, GCM projections agree in the direction and magnitude of temperature changes, but projections of precipitation change are more varied in both direction and magnitude (Barnett et al. 2005; Rodenhuis et al. 2007). Figures 3.24–3.28 in Chapter 3 ("Weather and Climate") illustrate anticipated climate changes for British Columbia, based on simulations by the Canadian Global Climate Model (CGCM2) for the A2 scenario.[9] The Canadian model tends to project warmer and wetter summers compared with the United Kingdom's Hadley Centre model (Spittlehouse 2008). Even under the low emissions scenario (B1), the amount of climate change projected for British Columbia by the end of the century (> 2° C; Figure 19.5, teal line) is comparable to the historical differences between the coldest of the cold years and the warmest of the warm years (troughs and peaks of solid black line); in other words, an entirely different temperature regime is projected for British Columbia than that of the last century.

The University of Victoria's Earth System Climate Model (ESCM; Eby et al. 2009) has also been run for

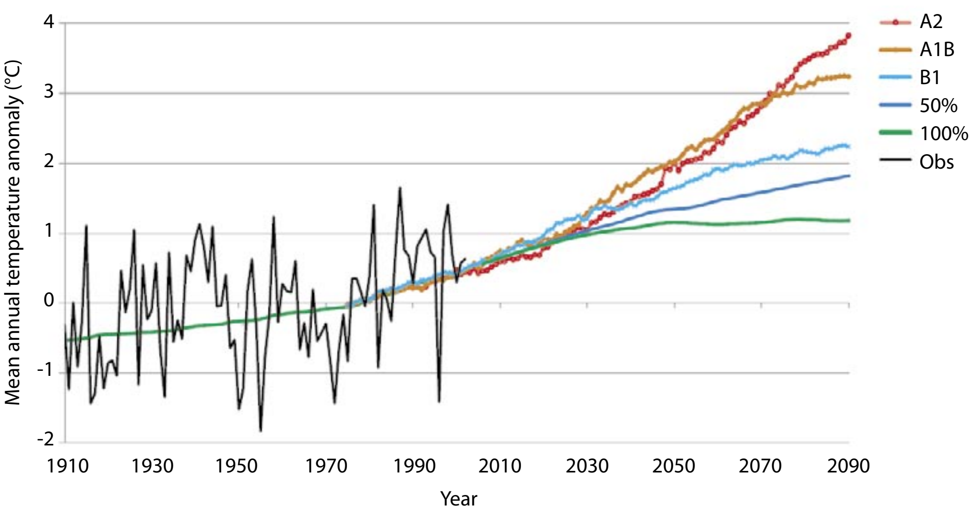


FIGURE 19.5 *Mean annual temperature anomalies for British Columbia using 1961–1990 baseline of the UVic ESCM over the 21st century for emission reduction scenarios compared to median of AR4 GCM projections for the A2, B1, and A1B SRES emissions scenarios. The GCM projections are displayed as 20-year centred means to remove annual and decadal variability. The 50% and 100% lines represent percent reductions by 2050; that is, to half of 2006 greenhouse gas emissions (blue) and to zero net emissions (carbon neutral; green). Sources: Environment Canada (historical data – CANGRID), Lawrence Livermore National Laboratory (GCM projections), and UVic Climate Modelling Lab (ESCM projections).*

8 SRES refers to the *Special Report on Emissions Scenarios*, published by the Intergovernmental Panel on Climate Change (IPCC) in 2000. For summary information about these scenarios, see Intergovernmental Panel on Climate Change (2007).

9 The A2 scenario is one of the highest emissions scenarios of the SRES group. In contrast, the B1 emission scenario represents roughly half of the emissions of A2.

several emissions that incorporate emissions reductions (Figure 19.5). It is reasonable to expect that the ESCM projections would be similar to those of an ensemble of several GCMs for similar emissions, as the ESCM follows the median of these GCMs for trajectories leading to similar greenhouse gas concentrations (not shown). These lower emissions are important because they represent the concentrations now the subject of serious policy debate. Importantly, Figure 19.5 shows that considerable climate change is projected for the province by the end of the century even under large emission-reduction scenarios, thus requiring adaptation.

2050s Projections for British Columbia

An ensemble of 30 projections from 15 GCMs was used to compute a range of projections for the 2050s (2041–2070) climate of British Columbia (Rodenhuis et al. 2007). Based on these results, the provincial annual average temperature is projected to warm by 1.7° C compared with the recent 1961–1990 period (Table 19.3; Figure 19.6). Uncertainty is represented by the range 1.2–2.5° C (the 10th–90th percentile of projections). The 2050s annual precipitation is projected to increase by 6%, with a range of 3–11%. The seasonal temperature projections were relatively uniform, but seasonal precipitation projections varied from 2% drier to 15% wetter for winter and 9% drier to 2% wetter for summer. Further information on model projections can be found in Rodenhuis et al. (2007). All models and emissions scenarios project an increase in winter and summer temperatures with the greatest increases for the higher emissions scenarios.

Regional 2050s Projections

At a regional scale, the same ensemble of 30 projections described above in "2050s Projections for British Columbia" (above) show that projected warming will be greater in the Interior than on the Coast (Table 19.3). Changes in precipitation will vary spatially as well as temporally. Southern and central British Columbia are expected to become drier in the summer, whereas northern British Columbia will likely become wetter (Table 19.3; see also Chapter 3, Figures 3.27 and 3.28). Overall, wetter winters are expected across British Columbia (Rodenhuis et al. 2007).

TABLE 19.3 *Changes in seasonal[a] and annual air temperature and precipitation by the 2050s for regions in British Columbia for the ensemble of 30 GCM projections described above in "2050s Projections for British Columbia" (updated from Rodenhuis et al. 2007)*

	Air temperature change (°C)				
Region	**Winter**	**Spring**	**Summer**	**Fall**	**Annual**
Columbia Basin	1.8	1.5	2.4	1.8	1.9
Fraser Plateau	1.9	1.6	2.0	1.8	1.8
North Coast	1.5	1.3	1.4	1.5	1.4
Peace Basin	2.4	1.7	1.8	1.8	1.9
Northwest	2.0	1.6	1.8	1.7	1.8
Okanagan	2.0	1.8	2.6	2.0	2.1
South Coast	1.5	1.3	1.7	1.6	1.5
British Columbia	*1.9*	*1.6*	*1.8*	*1.7*	*1.7*
	Precipitation change (%)				
Columbia Basin	7	9	−8	8	4
Fraser Plateau	8	10	−4	11	7
North Coast	6	7	−8	9	6
Peace Basin	9	9	3	10	7
Northwest	10	9	4	8	8
Okanagan	5	12	−8	8	5
South Coast	6	7	−13	9	6
British Columbia	*7*	*8*	*−3*	*9*	*6*

a Winter = December–February; Summer = June–August; Spring = March–May; Fall = September–November.

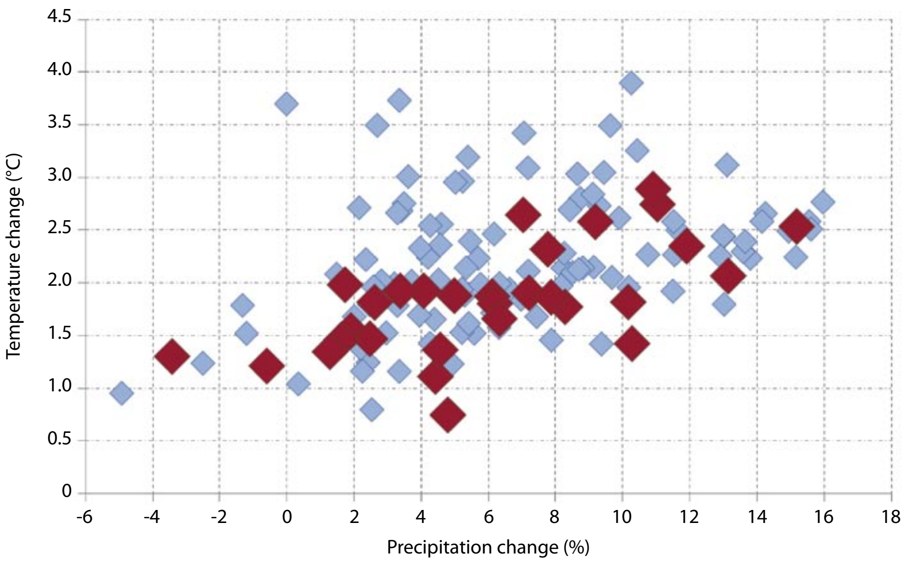


FIGURE 19.6 *Range of 2050s annual temperature and precipitation averaged over British Columbia from 140 GCM projections. The larger/darker diamonds represent the 30 projections in the ensemble described in the section "2050s Projections for British Columbia."*

Although we primarily present mean changes in climate in this chapter, future changes in the variability or the extremes of temperature and precipitation are anticipated to have many important effects on watershed processes. Changes in warm temperature extremes generally follow changes in the mean summer temperature (Kharin et al. 2007). This suggests that extreme maximum temperatures would be higher than at present and cold extremes would warm at a faster rate, particularly in areas that experience a retreat of snow with warming. An increase in the intensity and maximum amount of precipitation is also expected (Kharin et al. 2007); however, changes in extreme events may not be proportional to mean changes, and the changes may not be equal in both directions. For example, increasingly frequent extreme maximum temperatures are anticipated; however, the frequency of extreme cold temperatures is anticipated to decline in the future (Tebaldi et al. 2006; Kharin et al. 2007).

WATERSHED PROCESSES AFFECTED BY A CHANGING CLIMATE

It is expected that the effects of a changing climate on watershed processes will vary across British Columbia, depending on which specific watershed processes and responses are sensitive to change. In this section, we discuss the potential effects of a changing climate on watershed processes and outputs. Specifically, the following changes in watershed processes may be expected in British Columbia.

- Increased atmospheric evaporative demand
- Altered vegetation composition affecting evaporation and interception processes
- Decreased snow accumulation and accelerated melt
- Accelerated melting of permafrost, lake ice, and river ice
- Glacier mass balance adjustments
- Altered timing and magnitude of streamflow (peak flows, low flows)
- Altered groundwater storage or recharge
- Changes in frequency and magnitude of hillslope and geomorphic processes
- Changes in water quality, including increased stream or lake temperatures and altered chemical water quality

Atmospheric Evaporative Demand

Evaporative demand is a function of air and surface temperature, solar radiation, humidity, and wind speed (see Chapter 3, "Weather and Climate," and Chapter 6, "Hydrologic Processes and Watershed Response"). The climate scenarios previously described could increase the atmosphere's ability to evaporate water (Huntington 2008). This will occur if the saturation vapour pressure of the air (a function of air temperature) increases more rapidly than the actual vapour pressure (i.e., the vapour pressure deficit increases). It will also increase if net radiation and wind speed increase. An increase in evaporative demand would significantly affect water resources through evaporative losses from water bodies, vegetation, and soils, and through subsequent changes in water demands. Increased evaporative demand will also affect vegetation survival and growth through changes in water availability and fire risk. For example, Spittlehouse (2008) estimated the magnitude of change in evaporative demand (calculated following methods in Allen et al. 1998) for the Campbell River, Cranbrook, and Fort St. John areas using current weather station data and climate change model output for the B1 and A2 scenarios from the Canadian General Circulation Model (CGCM3). Evaporative demand, which is calculated for months when the air temperature is above 0° C, increased at all locations because of an increase in the length of time that air temperature remained above 0° C and an increase in the vapour pressure deficit (drier air). By the 2080s, evaporative demand increased by about 8% under the B1 scenario and by 15–20% under the A2 scenario (Spittlehouse 2008).

Estimates of evaporative demand and precipitation can be combined to give indicators of plant water stress and to predict water demand for agricultural irrigation and domestic use. A climatic moisture deficit occurs when the monthly precipitation is less than the evaporative demand for the month; conversely, if precipitation is greater than the evaporative demand, a moisture surplus occurs. By the 2080s under the B1 scenario, Spittlehouse (2008) reported that the deficit at Campbell River increased by 20%,[10] at Fort St. John by 25%, and at Cranbrook by 30%. For the A2 scenario, Campbell River and Fort St. John increased by 30%, whereas Cranbrook increased by 60%. The larger increase at Cranbrook reflects the decrease in summer rainfall and an initially relatively low average deficit for the 1961–1990 reference period. A moisture surplus did not occur during the summer at any of the locations for the climate change scenarios examined (Spittlehouse 2008).

Vegetation Composition Affecting Evaporation and Interception

Terrestrial vegetation influences water balance through the interception of rain and snow and the removal of water from the root zone as a result of plant transpiration and evaporation from the soil surface. As vegetation composition responds to climate change, so too will the amounts of water intercepted, evaporated, and transpired, thus altering snow accumulation and melt processes (see "Snow Accumulation and Melt," below), water balance, groundwater recharge, and ultimately streamflow and mass wasting processes. Increases in the length of the snow-free season and changes in atmospheric evaporative demand are likely to increase plant transpiration, assuming soil water is available. For example, Spittlehouse (2003) estimated that transpiration from a coastal Douglas-fir forest could rise by 6% with an increase of 2° C and by 10% with an increase of 4° C. The projected changes in climate are sufficient to affect forest productivity and species composition (Barber et al. 2000; Hamann and Wang 2006; Campbell et al. 2009). Changes may also occur in age-class distribution and in the form of vegetation (e.g., forest die-off, alpine encroachment, grassland expansion) (Breshears et al. 2005; Hebda 2007). Thus, changes to the amount of plant biomass on a site and the physiological characteristics of the new vegetation will have an important effect on water balance in the future.

Snow Accumulation and Melt

By the 2050s (2041–2070) increased air temperatures will lead to a continued decrease in snow accumulation (Rodenhuis et al. 2007; Casola et al. 2009), earlier melt (Mote et al. 2003), and less water stor-

10 Deficits are calculated for the months with an air temperature greater than 0°C. For Cranbrook, this is March to November, for Fort St. John, April to October, and for Campbell River, January to December. Formula are not appropriate for snow cover situations. Deficits occur only if monthly evaporation is greater than monthly precipitation. Cranbrook and Fort St. John have deficits in all months, whereas Campbell River has deficits only from May through September.

age for either spring freshet (Stewart et al. 2004) or groundwater storage. Changes in air temperature and wind may also affect snow adhesion in the snowpack and the subsequent amount of snow drift or scour that occurs in an area. “Wetter” snowpacks may be more resistant to redistribution by wind, which could be important for avalanche forecasting and management. The influence of vegetation on snow accumulation and melt processes (see Chapter 6, “Hydrologic Processes and Watershed Response”) will also be an important factor to consider as the composition of vegetation on the landscape changes. To simplify the discussion, we next consider the implications of increased temperature on snow processes.

Projected declines in snow are most notable on the central and north coast of British Columbia and at high-elevation sites along the south coast (Rodenhuis et al. 2007). Watersheds that may be the most sensitive to change are those occupying the boundary between rainfall and snow deposition in the winter (mixed regimes). For example, recent work in the Fraser River Basin (Figure 19.7) illustrates the 2050s changes in SWE projected by six different GCM emissions scenarios as a percentage difference from the 1961–1990 historical baseline period. These six sce-

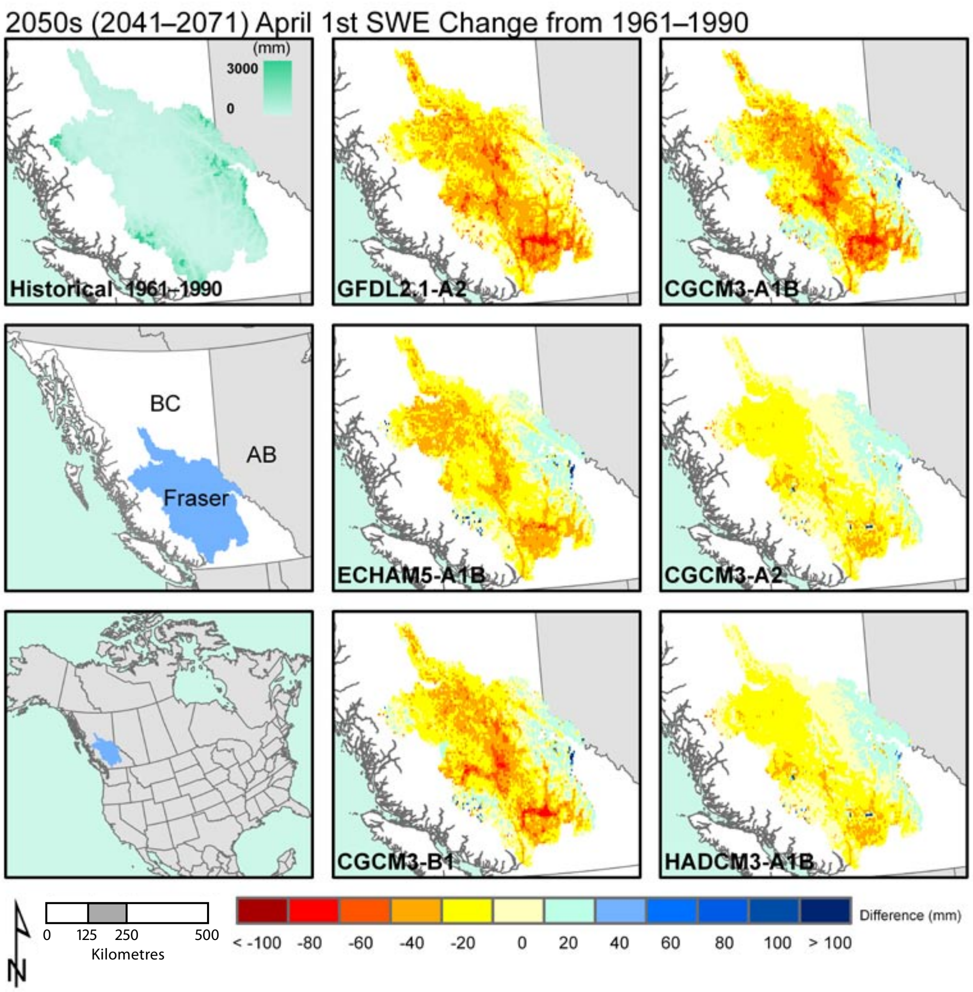


FIGURE 19.7 *Six GCM emissions scenarios projecting April 1st snow water equivalent (SWE) change to the 2050s in the Fraser River, British Columbia. Historical (1961–1990 April 1st) average SWE (mm) is illustrated in the top left-hand panel. The six scenarios are shown as 2050s (2041–2070) anomalies (mm) from the 1961–1990 baseline period on April 1st. For more information see “Case study: Fraser River Basin climate change projections,” page 719.*

narios include: Geophysical Fluid Dynamics Laboratory, version 2.1 (GFDL2.1-A2); Canadian Centre for Climate Modelling and Analysis, Canadian Global Climate Model, version 3 (CGCM3-B1, -A1B, -A2); Max Planck Institute for Meteorology, European Centre Hamburg Model, version 5 (ECHAM5-A1B); and Hadley / United Kingdom Meteorological Office, Hadley Centre Coupled Model, version 3 (HADCM3-A1B).

Snowpack is projected to decline in the central plateau region of the basin and increase in the upper reaches of the Rocky Mountains and at high elevations in the Coast Mountain ranges (Figure 19.7). Some variation is evident in the spatial distribution of change but, on average, models project a 28% decline in SWE by the 2050s across the Fraser River Basin. Projected increases in precipitation will only slightly offset the changes resulting from increased temperature alone (Table 19.3); however, if a large portion of winter precipitation shifts to rain, the amount and timing of discharge will significantly change (see discussion in "Streamflow: Peaks, Lows, Timing," below). For nival regimes, especially in southern British Columbia, the warming trend may result in an earlier freshet, leading to lower flows in late summer and early autumn (Loukas et al. 2002; Merritt et al. 2006). Hydrologic scenarios for snowmelt-dominated basins in the Okanagan are projected to change in this way (Merritt et al. 2006); however, the degree of change projected depends on the GCM used. Simulations performed by this chapter's authors found that, on average, snow disappeared 16 days earlier under 2° C of warming and 37 days earlier under 4° C of warming in the Okanagan Plateau region (Figure 19.8). The length of the snow season was reduced, on average, by 25 and 60 days under 2° C and 4° C of warming, respectively. Changes in seasonal snow accumulation and melt will result in changes to the streamflow regime, which has important implications for water supply, hydroelectric power, and fish and aquatic habitat.

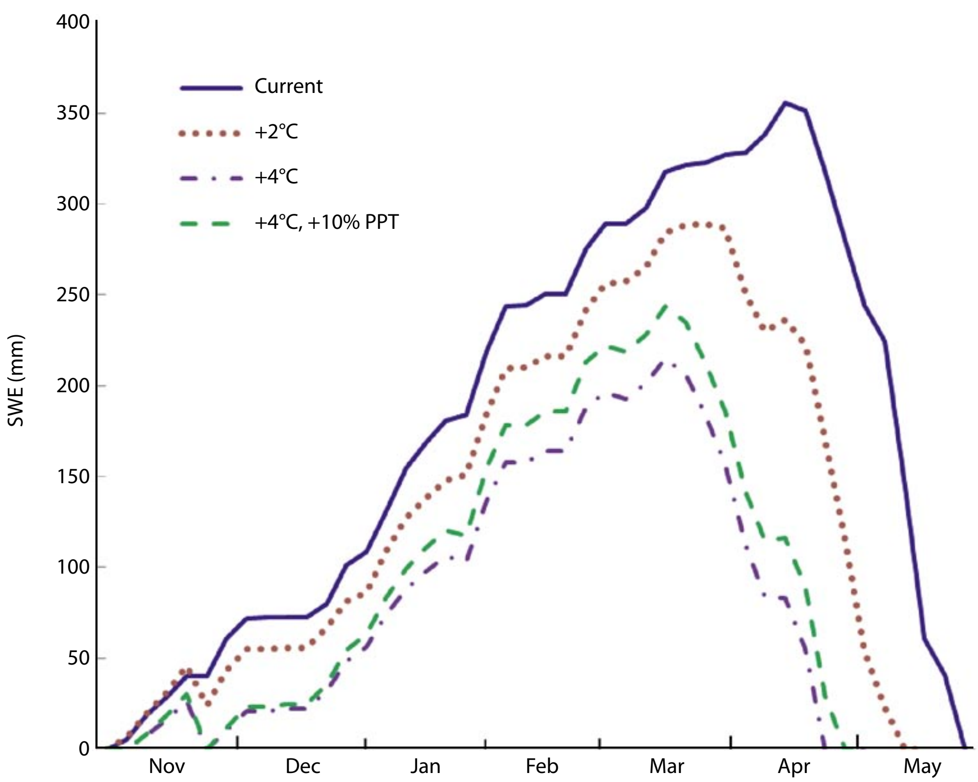


FIGURE 19.8 *Simulated winter snow water equivalent (SWE) in the mature lodgepole pine forest at the Upper Penticton Creek Experimental Watershed (1600 m elevation) under typical winter temperature and precipitation (2005–2006) conditions (solid blue line) and three climate change scenarios: (1) 2°C warming with no precipitation change (dotted red line); (2) 4°C warming with no change in precipitation (dashed and dotted purple line); and (3) 4°C warming with a 10% increase in precipitation (dashed green line).*

Less snow also has major implications for winter recreation and associated tourism activities (i.e. ski hills, Scott et al. 2006).

Permafrost, Lake Ice, and River Ice

Ice-related hydrologic features will be affected by rising temperatures. Projections of milder winter temperatures indicate that river and lake ice could occur later and disappear earlier than normal. These hydrologic changes will have implications for forest harvest scheduling (e.g., operable ground, seasonal water tables, timing), and transportation (e.g., ice bridges). In northern British Columbia, discontinuous permafrost is also expected to respond to temperature and precipitation changes. As with glaciers, all permafrost that exists today is not necessarily in equilibrium with the present climate. Unlike glaciers, however, adjustment to present climate lags on a longer time scale because of the insulating effects of the ground.

In the discontinuous permafrost region where ground temperatures are within 1–2° C of melting, permafrost will likely disappear as a result of ground thermal changes associated with global warming (Geological Survey of Canada 2006). In areas where the ice content is high, thawing permafrost can lead to increased thaw settlement and thermokarst activity, whereas reduced soil strength related to melting will lead to ground instability, increasing the incidence of slope failures (Smith and Burgess 2004). The integrity of engineered structures such as bridge footings, building foundations, roads, railways, and pipelines will also be affected (Woo et al. 2007).

Thawing permafrost may also affect aquatic ecosystems through changes to the storage and release of soil water (i.e., increasing the storage capacity) caused by the melting of ice. Under climate warming, the permanent thawing of permafrost may also add another source component to the hydrologic cycle. The overall thermal response of permafrost to increased temperatures will depend on the characteristics of the permafrost and surface buffer factors (e.g., snow, vegetation, and organic ground cover), which can attenuate temperature changes (Smith and Burgess 2004). The continuation of warming trends will likely increase the prevalence of thaw-related landslides in British Columbia and cause changes in soil water balances affecting the storage and release of water. About 50% of the Canadian permafrost region could ultimately disappear or become thinner in response to future climate warming (Smith et al. 2005).

Glacier Mass Balance Adjustments and Streamflow Response

Over the last few decades, the province's glaciers have dominantly had a negative mass balance (i.e., ablation of snow and ice exceeds the accumulation of snow) and continue to lose mass (Moore et al. 2009; Bolch et al. 2010; see also "Historical Trends in Snow, Seasonal Ice Cover, and Glaciers," above). Given future climate scenarios, glaciers will ultimately retreat under sustained conditions of negative net balance, although a lag is often associated with glacier dynamics (e.g., Arendt et al. 2002). Glacier retreat will continue until the glacier loses enough of its lower-elevation ablation zone that total ablation matches total accumulation. In some cases, climate warming can result in ablation exceeding accumulation over all elevations on a glacier, in which case the glacier would ultimately disappear. This will likely occur for glaciers in Montana's Glacier National Park and the North Cascades in Washington (Hall and Fagre 2003; Pelto 2006).

Projections based on future climate scenarios indicate that a negative net balance will continue over at least the next few decades. Hall and Fagre (2003) modelled glacier response to climate change in Montana's Glacier National Park under two climate scenarios. In the first scenario, with a doubling of CO_2 and a summer mean temperature increase of 3.3° C, all glaciers disappeared by 2030. In the second scenario, with a linear increase in temperature over time and a 0.47° C increase in summer mean temperature, glaciers remained until 2277. Stahl et al. (2008) used three scenarios to model the response of the Bridge Glacier in the southern Coast Mountains: one was a continuation of current climatic conditions until 2150, and two others were based on the A2 and B1 emissions scenarios developed by the Intergovernmental Panel on Climate Change (IPCC 2007) and simulated by the CGCM3. Even with no further climate warming, the Bridge Glacier is sufficiently out of equilibrium with current climatic conditions that it is projected to lose approximately 20% of its current area, reaching a new equilibrium by about 2100. Under the two warming scenarios investigated, glacier net balance remained negative and the glacier continued to retreat over the next century, with a projected loss of over 30% of its current area by the end of this century.

If glaciers are initially in equilibrium with current climatic conditions (i.e., snow accumulation balances ablation of snow and ice), then the onset of climatic warming will produce an initial increase in glacial melt and runoff contributions to streamflow (Hock et al. 2005; Moore et al. 2009). This increase in melt results from a lengthening of the melt season (i.e., advanced onset of melt in spring, delayed onset of accumulation in autumn) and an increase in melt intensity, particularly as firn (snow deposited in previous years) melts away, exposing the less reflective glacier ice to solar radiation. Eventually, however, the loss of glacier area will reduce total meltwater generation, resulting in a decrease in glacier runoff contributions to streamflow. Although this pattern of response to climate warming is generally accepted, the time scale over which the response shifts from increasing to decreasing discharge is not known.

Negative trends have been documented for summer streamflow in glacier-fed catchments in British Columbia, with the exception of the northwest, where streamflow has been increasing in glacier-fed catchments (Fleming and Clarke 2003; Stahl and Moore 2006). Similar negative trends have been documented for the late summer to early autumn "transition to base flow" period for glacier-fed headwaters draining the eastern slopes of the Canadian Rocky Mountains (Demuth and Pietroniro 2001; Comeau et al. 2009). Thus, it appears that the initial phase of streamflow increases associated with accelerated glacier melt has already passed for most of the province, whereas the northwest is still experiencing augmented streamflow. Stahl et al. (2008) found that future glacier retreat produced continuing declines in summer flows for Bridge River, particularly for July to September.

In addition to changes in streamflow, future glacier retreat will influence a range of aquatic habitat characteristics, including stream temperature, suspended sediment concentrations, and stream water chemistry. It is possible that the number and rates of geomorphic events or processes associated with glacial retreat will also increase in the future (see "Changes in Geomorphic Processes," below). Reduced glacier cover will also affect tourism and outdoor recreation activities in much of the province. Physical considerations and empirical evidence consistently indicate that summer stream temperatures should increase as a result of glacier retreat; however, the magnitude of this change is difficult to predict. Changes in other aspects of aquatic habitat will depend on a range of site-specific factors, and generalizations, even about the direction of change, cannot be made with confidence (Moore et al. 2009).

Altered Groundwater Storage and Recharge

The most direct interaction between climate and groundwater is through the process of recharge, which occurs when water from the ground surface (i.e., precipitation inputs, surface water bodies) has percolated to the water table. Recharge is the net result of energy and moisture transfer that occurs at the land surface, and is controlled by climate, vegetation, topography, soil characteristics and physical characteristics of the aquifer (i.e., geology). Thus, the recharge process will exhibit different degrees of sensitivity to the state of climate in a given region. Decreased recharge and persistent declines in groundwater storage can lead to a reduction in water supplies, degradation of water sources for groundwater-dependent ecosystems, land subsidence, increased conflicts between water users, and saltwater intrusion in coastal areas (Rivera et al. 2004). Groundwater discharge to streams is a critical factor governing low flows across much of British Columbia, with steeper mountain areas typically having little groundwater storage capacity (periodically leading to drying streams in the summer), and larger valleys with deeper alluvial sediments providing greater groundwater contributions through the low-flow period (Burn et al. 2008).

Changes in recharge fluxes will be influenced by several of the previously discussed processes, including increased atmospheric evaporative demand, changes in vegetation composition, snow accumulation and melt, and streamflow. Changes in the amount, timing, and form of precipitation (snow vs. rain) will all affect the rate and timing of groundwater recharge. Changes to streamflow will also affect groundwater recharge in locations where surface water is the main recharge source (i.e., alluvial valley-bottom aquifers recharged by streamflow during periods of high flow and discharge to streams during low flow periods). Depending on aquifer size and depth, any changes in groundwater hydrology caused by change in climate will likely occur more slowly than surface water changes.

The physical characteristics of aquifers have a strong influence on how groundwater systems respond to climatic changes. For example, shallow aquifers with highly permeable sediments (e.g., fractured bedrock or unconsolidated coarse sediments) are more responsive to climatic changes than deeper bedrock aquifers (Rivera et al. 2004). Deeper aquifers have a greater ability to buffer short-term perturbations; however, these aquifers will also preserve the signature of longer-term trends in climate change.

Relatively little research has been directed toward the effects of climate change on groundwater in British Columbia (Allen 2009) or elsewhere in the world (Dragoni and Sukhija [editors] 2008; GRAPHIC Team 2009). Provincial research consists of case studies of the Grand Forks Aquifer (Allen et al. 2003; Scibek and Allen 2006a, 2006b; Scibek et al. 2007), the Abbotsford-Sumas Aquifer (Scibek and Allen 2006a), the Okanagan Valley (Toews and Allen 2009; Toews et al. 2009), and the Gulf Islands (Appiah Adjei 2006). From these studies, the authors concluded that groundwater resources in the southern Interior are potentially the most sensitive to climate change in British Columbia. This is because of the strong influence of snow accumulation and melt on recharge and the potential changes in the magnitude and timing of nival processes under future climates (Allen 2009). Nevertheless, the estimated changes in groundwater storage and recharge are within the uncertainty range of the groundwater and GCM models (Allen 2009), which makes it difficult to identify or predict actual climate change influences (GRAPHIC Team 2009).

For the Grand Forks Aquifer, research combining GCM projections and groundwater models indicates that peak runoff in the Kettle River would occur earlier, and that the shift in peak streamflow would be accompanied by an earlier annual peak in groundwater levels. Away from the floodplain, groundwater recharge is predicted to increase in spring and summer months, and decrease in winter months (Scibek et al. 2007).

Research in the Okanagan Valley shows that direct (vertical) recharge along the valley bottom is driven largely by regional precipitation (e.g., frontal precipitation) rather than localized precipitation (e.g., convective storms) (Toews et al. 2009). When combined with future climate scenarios, peak recharge is expected to occur earlier in the year when evaporative demand is lower. The net effect is a minor increase in annual recharge for predicted future climate scenarios (Toews and Allen 2009), which could possibly buffer higher water demand in hotter and drier summer months in this region.

The potential effects of climate change on groundwater levels and recharge in the Lower Mainland and coastal regions generate fewer concerns. A modelling study of the Abottsford-Sumas Aquifer indicates only small absolute decreases in water levels, which are generally limited to upland areas (Scibek and Allen 2006a). However, lower groundwater levels will result in decreased base flow during low flow periods, which may have a negative influence on fish habitat. For aquifers on the Gulf Islands and in other coastal locations, concerns about decreasing recharge and declining water levels are related to the potential for saltwater intrusion (Rivera et al. 2004), a problem that may be compounded by rising sea levels (Allen 2009). In combination, a decrease in groundwater recharge and increase in sea level will cause the interface between seawater and fresh groundwater to move further inland, potentially increasing aquifer salinity to a point where its water is not fit for human consumption or use in irrigation.

Assessing the effects of climate change on groundwater is a difficult task because highly detailed subsurface information is required to develop quantitative models (Allen 2009). The aquifer classification system for the Canadian Cordillera (Wei et al. 2009) could be used as a starting point to identify the aquifer types with the greatest potential to be affected by climate change. Several successful attempts have been made to quantify areal or regional changes in groundwater storage using the Gravity Recovery and Climate Experiment (GRACE). Essentially, GRACE satellites record changes in Earth's gravity field that are then related to changes in terrestrial water storage (Rodell and Famiglietti 2002). This technique has been applied on the Canadian Prairies (Yirdaw et al. 2008) and the Mackenzie River basin (Yirdaw et al. 2009). Although these applications of GRACE data are encouraging, further research and testing is required to determine whether the method is appropriate for the complex physiography and geology of British Columbia and whether the impact of climate variation on groundwater can be determined at a resolution useful for water management.

Streamflow: Peaks, Lows, and Timing

Streamflow regimes are controlled primarily by seasonal patterns of temperature and precipitation, as well as watershed characteristics such as glacier cover, lake cover, and geology. In British Columbia, the four main hydrologic regimes are: (1) rain-dominated, (2) snowmelt-dominated, (3) mixed/hybrid, and (4) glacier-augmented (see Chapter 4, "Regional Hydrology"). The relative importance of climatic changes, therefore, will vary by region and depend on the current sensitivity of the hydrologic regime to regional temperature and precipitation changes. Also, groundwater storage and release strongly control streamflow (particularly low flows) in some watersheds (see discussion above). Variations in underlying geology that influence whether snowmelt goes into groundwater reserves or directly into runoff can determine the magnitude and timing of late-summer streamflow, and thus affect the overall response to climate change (Thompson 2007; Tague and Grant 2009).

The hydrologic effects of climate change will have an important influence on all types of watersheds, not just those with cold-season precipitation storage as snowpack. The response of rain-dominated regimes will likely follow predicted changes in precipitation (Loukas et al. 2002). For example, increased magnitude and more numerous storm events will result in increasingly frequent and larger storm-driven streamflow (including peaks) in the winter. Projected warmer and drier summers also raise concerns about a possible increase in the number and magnitude of low flow days.

Projected warming will result in less snow stored over winter (Figures 19.7 and 19.8) and more winter precipitation falling as rain. In these situations, hybrid/mixed regimes might transition to rain-dominated regimes through the weakening or elimination of the snowmelt component (Whitfield et al. 2002). Similarly, snowmelt-dominated watersheds might exhibit characteristics of hybrid regimes and glacier-augmented systems might shift to a more snowmelt-dominated pattern in the timing and magnitude of annual peak flows and low flows. For example, in the southern Columbia Mountains at Redfish Creek, an increase is evident in the incidence of fall to early-winter peak streamflow events, which up to 10 years ago were relatively rare in the hydrometric record (P. Jordan, Research Geomorphologist, B.C. Ministry of Forests and Range, pers. comm., Dec. 2007). With projected elevated temperatures, the snow accumulation season will shorten (Figure 19.8) and an earlier start to the spring freshet in snowmelt-dominated systems will likely occur, which may lengthen the period of late-summer and early-autumn low flows (Loukas et al. 2002; Merritt et al. 2006). Where snow is the primary source of a watershed's summer streamflow, loss of winter snowpack may reduce the late-summer drainage network, transforming once perennial streams into intermittent streams (Thompson 2007). Conversely, where groundwater is the primary source of a watershed's summer streamflow, flows will still continue but with volume reductions in response to changes in the seasonal snowpack accumulation that recharges groundwater (Thompson 2007).

In glacier-augmented systems, peak flows would decrease and occur earlier in the year, similar to snowmelt-dominated regimes. In the long term, the reduction or elimination of the glacial meltwater component in summer to early fall would increase the frequency and duration of low flow days in these systems.

In hybrid regime watersheds on the Coast, some snowpacks above 1000–1200 m can be up to 4–5 m deep (e.g., Russell Creek), especially in north-facing open bowls or subalpine forests (B. Floyd, Research Hydrologist, B.C. Ministry of Forests and Range, pers. comm., 2007). Normally, snowpacks in these hybrid regimes are deep enough to store a significant amount of rain, thus dampening the response of watersheds to large midwinter rain events. If these snowpacks no longer form or are very shallow, and increases in temperature and wind speeds occur, large midwinter snowfall events will become large rain or melt events, and thereby increase the frequency of high flows occurring throughout the winter in these watersheds. Subsequently, spring peak flow volumes will decrease and occur earlier because less precipitation is stored as snow during the winter, and winter flows will increase because precipitation will fall as rain instead of snow.

For all streamflow regimes, a complex relationship will likely develop between rain-on-snow events and changes in regional air temperature and precipitation patterns. This is because the magnitude of rain-on-snow floods fluctuates depending on the duration and magnitude of precipitation, the extent and water equivalent of the antecedent snowpack, and the variations in freezing levels (McCabe et al. 2007). Climatic changes will influence all of these factors. For example, McCabe et al.'s (2007) modelling study showed that as temperatures increase, rain-on-snow events decrease in frequency primarily at low-elevation sites. Higher elevations are likely less sensitive to changes in temperature as these sites remain at or below freezing levels in spite of any temperature increase that would affect snow accumulation (McCabe et al. 2007).

Case study: Fraser River Basin climate change projections

The Fraser is one of British Columbia's largest rivers, and one of the most productive salmon rivers in the world. Approximately two-thirds of B.C.'s population resides in the basin, and 80% of the provincial economy is generated within the basin. Because of its importance to the residents of British Columbia, concerns have been raised over the effect of future climatic changes in the basin. To address some of these concerns, the Fraser River Basin was modelled using the semi-distributed, Variable Infiltration Capacity (VIC) hydrologic model (Liang et al. 1994, 1996; Schnorbus et al. 2009). The aim of this computer modelling was to examine the impacts of climate change on basin hydrology for the 2050s (i.e., the period of 2041–2070 from the baseline period of 1961–1990). Although the hydrologic impacts of climate change in British Columbia have been examined (e.g., Slaymaker 1990; Brugman et al. 1997; Whitfield and Taylor 1998; Loukas et al. 2002; Whitfield et al. 2002; Merritt et al. 2006; Toth et al. 2006), only three studies have specifically presented results for the Fraser River Basin (i.e., Moore 1991; Coulson 1997; Morrison et al. 2002).

Creating projections of future streamflow and snowpack conditions across the entire Fraser River Basin is valuable for several reasons. For example, the distributed hydrologic model produces simulations at various spatial and temporal scales. To estimate projected streamflow responses for specific watersheds, the model "forces" future simulations with temperature and precipitation downscaled from gridded GCMs. By examining a suite of GCMs and emissions scenarios, it is possible to analyze a range of potential futures for the Fraser River Basin. This approach to modelling provides practitioners with valuable information to support planning initiatives and to develop suitable adaptation plans for the Fraser River Basin.

The work we present here applies the bias-corrected spatial downscaling technique to estimate future temperature and precipitation change for six GCM emissions scenarios selected from the IPCC's fourth assessment report database (see Intergovernmental Panel on Climate Change 2007). This particular subset of the GCMs performs well across North America when compared to historical data (Plummer et al. 2006; Salathé et al. 2007; Gleckler et al. 2008). The six scenarios described in "Snow Accumulation and Melt," (above) were chosen to represent a wide range in future conditions, from warm-wet to cool-dry climates occurring in the Fraser River watershed. Downscaling measures included bias-correction of the monthly "coarse"-resolution GCM emissions scenarios model output to match the spatial and temporal resolution of the VIC hydrologic model (based on methods described by Wood et al. 2002; Widmann et al. 2003; Salathé 2005; see also "Downscaling for Watershed Modelling," below). These downscaled forcings were used to run the VIC model out to the year 2100 across the entire 225 000 km^2 Fraser Basin above Hope, at a grid-scale resolution of approximately 32 km^2 (as described in Schnorbus et al. 2009). This updates previous work by employing the latest GCMs as well as a statistical downscaling technique that produces a bias-corrected transient simulation on a monthly basis for the entire distribution, gridded to the scale of the hydrologic model resolution (32 km^2). For the historical baseline period, the model performance was 0.89 for the calibration period (1985–1990) and 0.82 for the validation period (1991–1995) based on Nash-Sutcliff model efficiency (Nash and Sutcliffe 1970).

Future projected changes for the Fraser River Basin by the 2050s include an increase in median annual precipitation of 5% and potential increase in median annual air temperature of 2° C. Figure 19.9 presents winter and summer scatterplots for all IPCC SRES AR4 GCMs along with the selected GCM and emissions scenarios for precipitation against temperature as projected anomalies from the historical baseline. Figure 19.10 shows the projected increase in annual mean air temperature by the 2050s, an increase that is observed across all six scenarios. Across most models, the warming is greatest in the Thompson-Nicola region in the southeastern part of the basin. The median summer (June–August) air temperature is projected to increase by 3–4° C. Although the southern portion of the basin will warm faster than the north in the summer, the strongest winter warming is projected for the northern region of the basin (e.g., in the Stuart River watershed above Fort St. James, 2.6° C). Figure 19.11 illustrates the projected increase in annual median precipitation across the basin, although some scenarios show a small decrease in the southern part of the basin, including the Chilcotin Plateau and the Thompson-Nicola region. Most model projections illustrate an increasing gradient of precipitation to the northeast of the basin, with the least amount of precipitation change projected for the southwestern portion of the Fraser along the Coast Mountain ranges (8%). Summer precipitation change is projected to decrease in most scenarios, although the ECHAM5-A1B scenario projects a wetter summer in the northern watersheds near Quesnel.

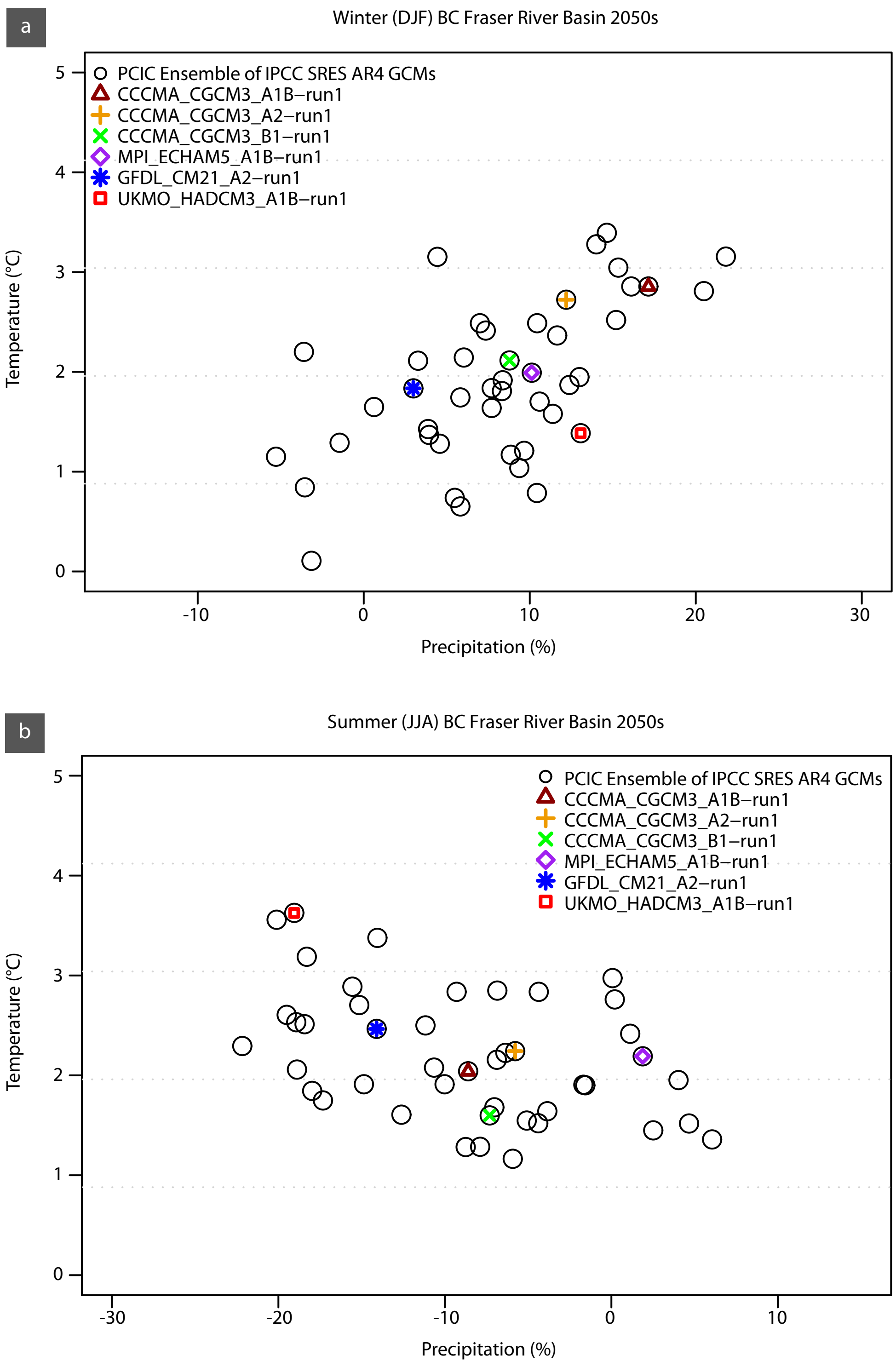


FIGURE 19.9 *Scatterplots of (a) winter and (b) summer precipitation versus air temperature projections for the Fraser River Basin provided by the six GCM emissions scenarios. The modelling centre is identified in the legend followed by the GCM name/version: CCCMA – Canadian Climate Centre for Modelling and Analysis; MPI – Max Planck Institute; GFDL – Geophysical Fluid Dynamics Laboratory; UKMO – United Kingdom Meteorological Office.*

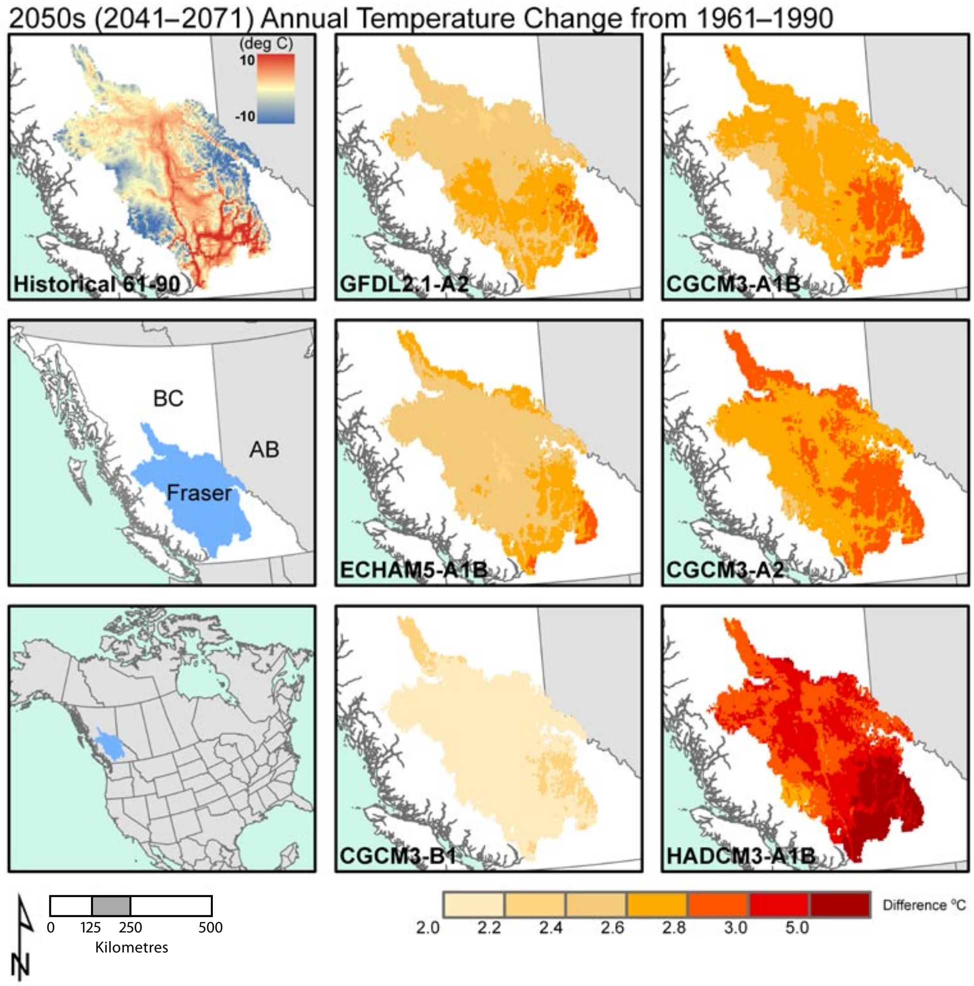


FIGURE 19.10 *Six GCM emissions scenarios projecting annual air temperature changes to the 2050s in the Fraser River Basin. Historical temperatures are illustrated in the top left-hand panel. The six scenarios are shown as degree Celsius anomalies from the 1961–1990 baseline period.*

For the most part, these projections agree with findings from previous work but with some differences. Morrison et al. (2002) projected an increase in mean annual air temperature of 1.5° C with the CGCM1 doubled CO_2 simulation, which is similar but lower than the CGCM3-B1 emissions scenario projection we present here for the Fraser Basin. Moore (1991) based his analysis on GCM projections provided in Slaymaker (1990), which selected "boundary" model results, estimating that temperatures would increase by 2.4–6° C in the winter and 0.6–4.2° C in summer. Moore's (1991) precipitation projections ranged from no change at all to increases of 15% and 20%, which is similar to the wet ECHAM5-A1B and CGCM3-A1B GCM emissions scenarios presented here. Coulson's (1997) projection for a 9% increase in precipitation for Prince George is also within the range represented by the six scenarios analyzed here. Morrison et al. (2002) projected approximately a 15 % increase (decrease) in winter (summer) precipitation at Kamloops, which is similar to the winter projections provided here; however, the summer decrease may be too extreme, based on the downscaled projections analyzed in this study. Differences in the projections may be partly attributable to the GCM versions applied in previous studies (e.g., CGCM3 vs. CGCM1), and the use of new transient emissions scenarios (SRES vs. doubled CO_2) applied in this case study.

Basin-wide annual runoff projections for the 2050s range from –20% in some watersheds to +35% by the CGCM3-A1B scenario (Figure 19.12). The drier scenarios (i.e., GFDL2.1-A2 and HADCM3-A1B) project

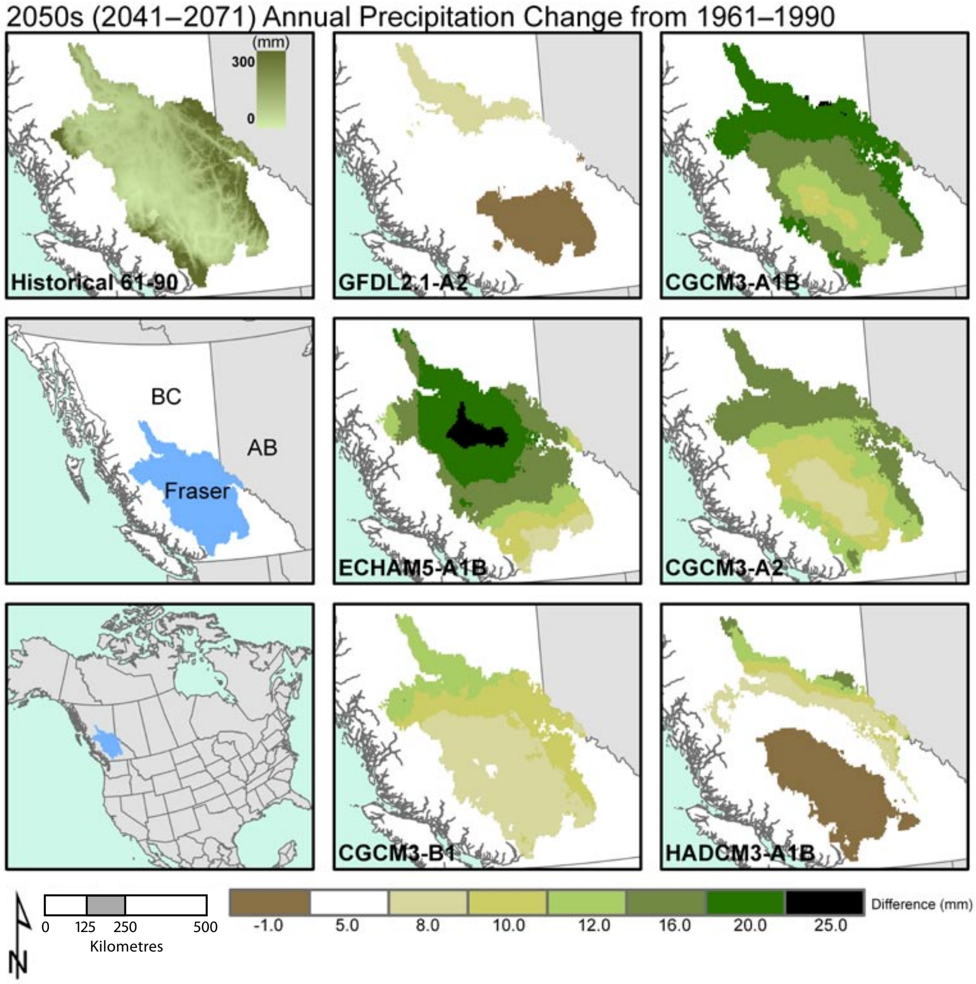


FIGURE 19.11 *Six GCM emissions scenarios projecting annual average precipitation changes to the 2050s in the Fraser River Basin. Historical precipitation (mm) is illustrated in the top left-hand panel. The six scenarios are shown as percentage differences from the 1961–1990 baseline period.*

a decline in annual runoff through the southern plateau regions of the Basin, in the Cariboo-Chilcotin region (including West Road River and Baker Creek), and into the lower reaches of the Thompson River watershed. Notably, most of the scenarios project a positive runoff condition for the future in the northern reaches of the watershed above Prince George, which reflects the projected 16% increases in runoff estimated by Colson (1997). A 14% increase in runoff is projected for the Fraser River at Hope, although projections range from almost no change in runoff (1%, GFDL2.1-A1B) to a larger increase (23%, CGCM-A1B), with a standard deviation between scenarios of 8%. On a seasonal basis, flows for the Fraser at Hope are projected to increase by approximately 1500 m^3/s in the spring, and decrease by approximately 1400 m^3/s in the summer on average (Figures 19.13 and 19.14).

Most scenarios project winter runoff increases, but some scenarios (i.e., GFDL2.1-A2, HADCM3-A1B) project a drier winter for the headwater basins of the Cariboo-Chilcotin region (Figure 19.15). Decreases in runoff for these models correspond to moderate increases or slight decreases in annual precipitation and declines in fall soil moisture (results not shown). The median winter 2050 projection for the Fraser Basin illustrates large increases in runoff (100% or greater) for mid-elevation reaches along the Rocky Mountain headwater regions, as opposed to the Coast Mountains, where slight decreases are projected by the 2050s. Increases in runoff correspond to a 25% increase in the winter precipitation for

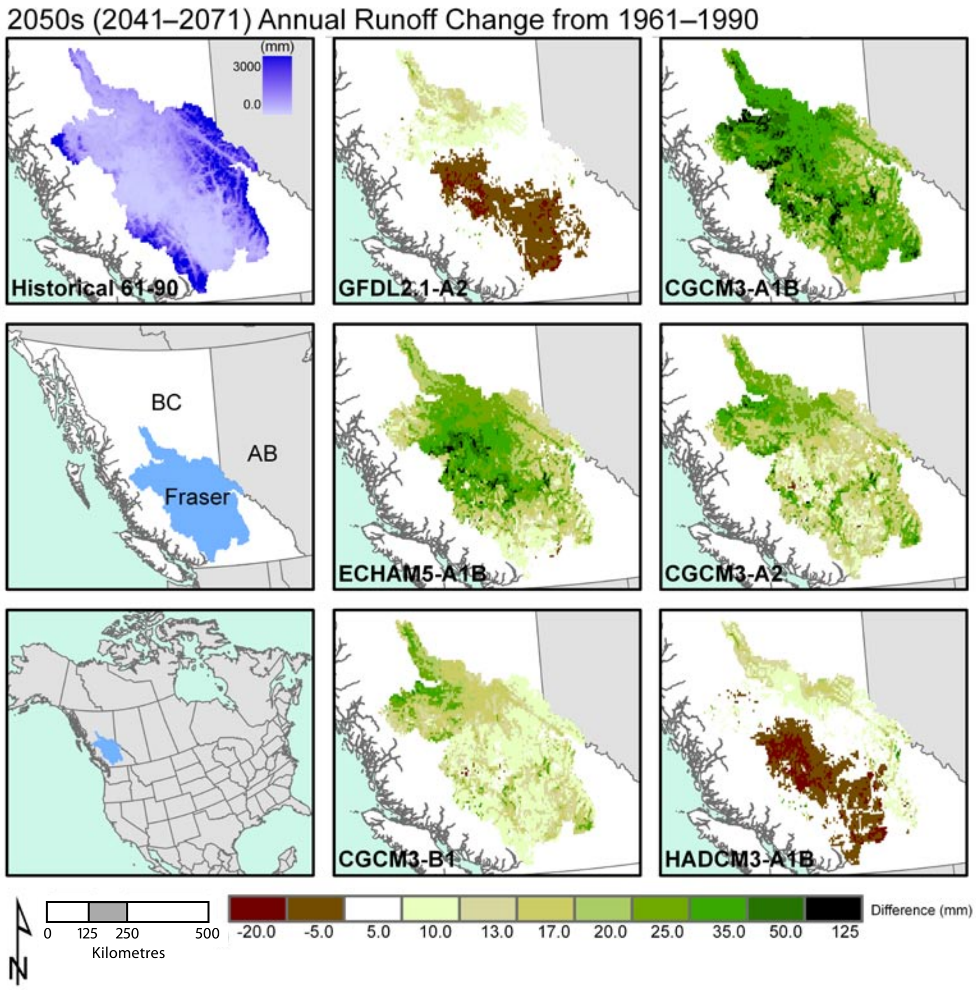


FIGURE 19.12 *Six GCM emissions scenarios projecting annual average runoff changes to the 2050s for the Fraser River Basin. Historical runoff (mm) is illustrated in the top left-hand panel. The six scenarios are shown as percentage differences from the 1961–1990 baseline period.*

the Rocky Mountains. The median summer runoff projection (Figure 19.14) is drier for most areas of the basin, especially in the watersheds of the Quesnel, McGregor, Salmon, and South Thompson Rivers. Projections for the lower reaches of the Thompson River watershed appear to have virtually no change in runoff for almost every scenario (Figure 19.14).

These runoff projections corroborate with Morrison et al.'s (2002) results with some important deviations. The Morrison et al. study (2002) indicated that the change in peak flow is projected to decline into the future, whereas the modelled flows presented here are projected to increase. This important difference may be caused by the higher precipitation amounts (particularly in the spring) projected by the more recent, transient SRES emissions scenarios. Additionally, the Morrison et al. study may have underestimated precipitation distributions across the high-elevation regions of the Fraser Basin, whereas the gridded downscaling approach of the VIC model allows for a more accurate analysis of high-elevation regions and shows these areas as receiving increased amounts of precipitation (still falling as snow) by the 2050s. This can be seen in the April 1st SWE maps where high-elevation sites in the Rocky and Coast Mountain ranges experience slight increases in snowpack (see Figure 19.7). However, the different tools and modelling approaches used in each study prevents a definitive explanation of why these model projections are so divergent.

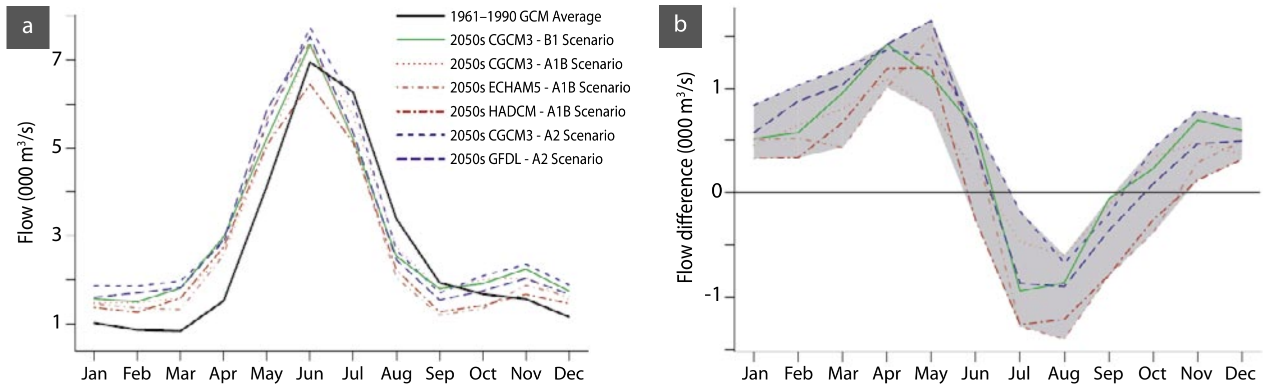


FIGURE 19.13 *Fraser River streamflow: (a) future projections of Fraser River streamflow at Hope, with the 1961–1990 baseline period (average of all GCMs) depicted by a black line; (b) differences in streamflow from the baseline period with the range in GCM emissions scenarios shown in grey to illustrate the variation across the scenarios.*

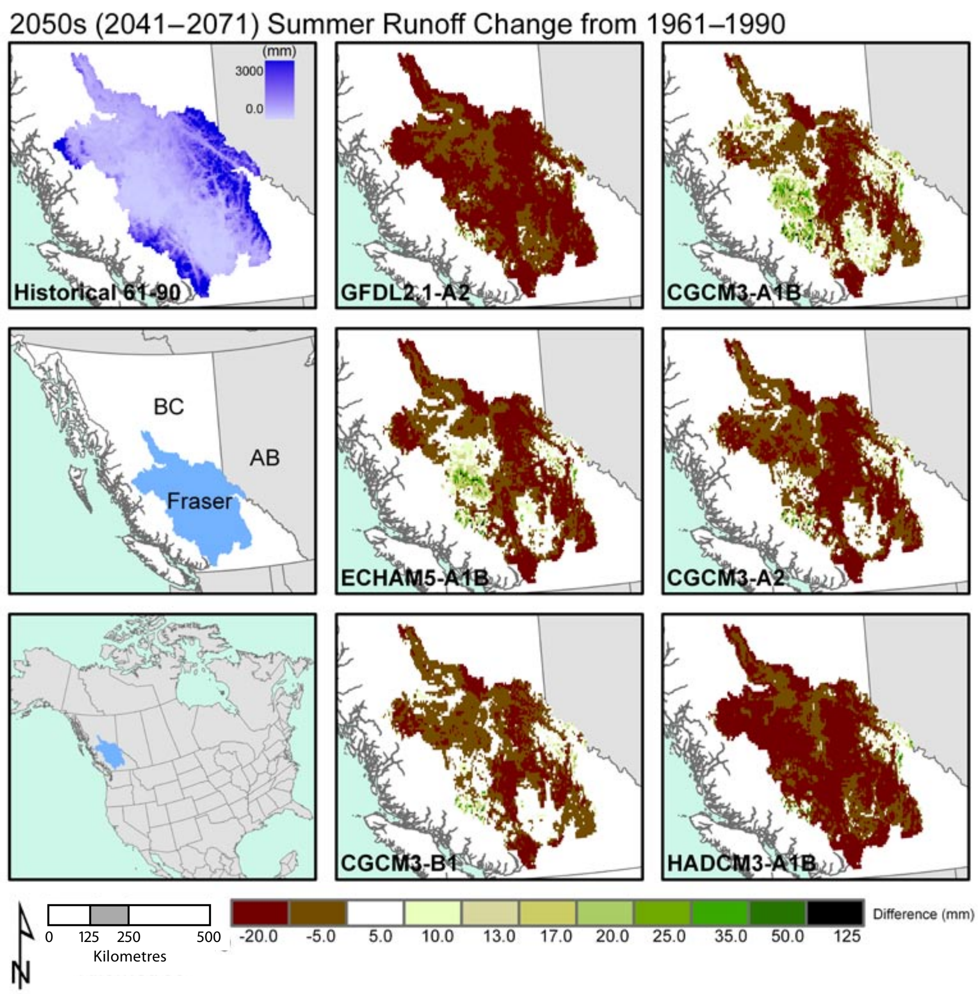


FIGURE 19.14 *Six GCM emissions scenarios projecting summer (JJA) runoff changes to the 2050s for the Fraser River Basin. Historical runoff (mm) is illustrated in the top left-hand panel. The six scenarios are shown as percentage differences from the 1961–1990 baseline period.*

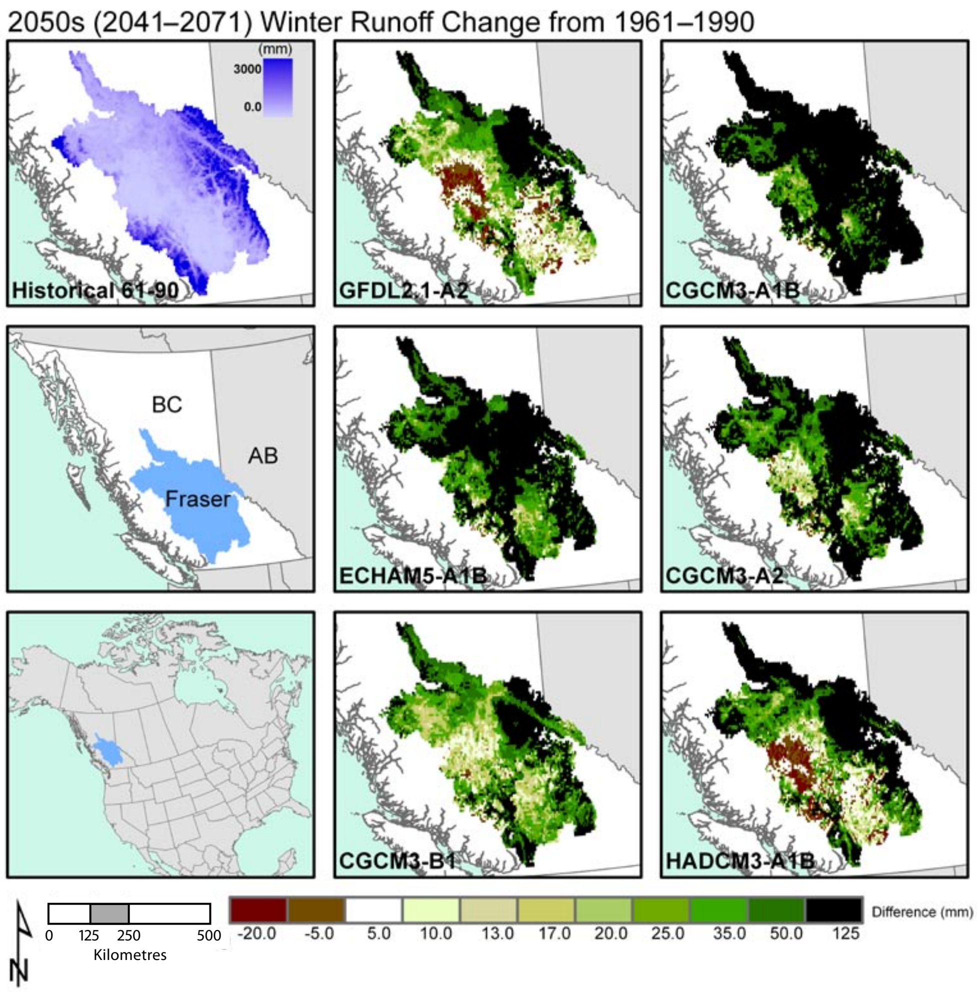


FIGURE 19.15 *Six GCM emissions scenarios projecting winter (DJF) runoff changes to the 2050s for the Fraser River Basin. Historical runoff (mm) is illustrated in the top left-hand panel. The six scenarios are shown as percentage differences from the 1961–1990 baseline period.*

Changes in Geomorphic Processes

Landslides in British Columbia are driven by climate, topography, geology, and vegetation. Landslide response to climatic changes will vary depending on the type of landslide and the initiation process (Geertsema et al. 2007; and see Chapter 8, "Hillslope Processes," and Chapter 9, "Forest Management Effects on Hillslope Processes"). Future changes in geomorphic processes will be driven primarily through changes in precipitation and temperature regimes. Recent trends, as detailed above in "Historical Trends in Landslides and Other Geomorphic Processes," are expected to continue.

In northern British Columbia, shallow slides and debris flows happen during infrequent large storms; large rock slides appear to respond to warming and may be triggered during convective storms; and larger soil slides are more common during periods of increasing precipitation (Egginton et al. 2007; Geertsema et al. 2007; and "Historical Trends in Landslides and Other Geomorphic Processes," above). Long-term increases in temperature and precipitation may be preconditioning slopes to fail, whereas intense or large-scale storms may also be triggers of such failures (Egginton 2005). Both scenarios are expected to increase with future climatic changes.

In coastal British Columbia, debris slide and debris flow initiation typically occurs during high-intensity precipitation events, often augmented with additional input from snowmelt, which occurs during fall or winter frontal storm systems. Predictions of the influence of projected climate changes to precipitation have typically focussed on average precipitation and long-duration conditions rather than extreme or short-duration events. As such, regional predictions of changes in precipitation intensity–duration relationships remain a significant knowledge gap in British Columbia, particularly for durations shorter than 24 hours. Landslide response to climate change in these areas will largely follow the projected peak flow response in rain-dominated and hybrid streams. In the Georgia Basin, for example, relationships between annual precipitation and short-duration precipitation intensity were examined by Miles as a predictive approach to estimating changes in storm frequency.[11] For 24-hour rainfall events sufficiently large enough to initiate slope failures, the reported 10% increase in annual precipitation over 80 years could lead to a decrease in storm return periods from 10.4 to 6.3 years.[12] Similarly, Jakob and Lambert (2009) correlated GCM modelling with antecedent precipitation and short-duration rainfall observations to evaluate projected changes in landslide initiation in southwest British Columbia. They estimated that a 6–10% increase in antecedent and short-duration precipitation amounts by the 2071–2100 period could lead to expected increases in landslide initiation of 28%.

Ongoing glacial recession will continue to promote periglacial processes in recently deglaciated areas. This includes increased geomorphic hazards such as outburst flooding, rock debuttressing, slope failures on over-steepened slopes, changes to sediment production, and suspended sediment fluxes (Moore et al. 2009).

Snow avalanche activity will likely also be affected through various processes that are forecast to change; however, the overall implications are likely complex and variable. Increased storm intensities during the winter may lead to increased avalanche activity. Countering this process will be warmer-than-present winter temperatures which, in general, will result in lower temperature gradients within snowpacks, and therefore increased slope stability. This may have a more pronounced effect for Interior ranges and northern British Columbia, which currently have very cold winters and typically strong snowpack temperature gradients. In some areas, the winter snow line may migrate high enough so that lower-elevation areas do not exceed threshold snow depths sufficient to initiate avalanches. This upward migration of the snow line, and encroachment of vegetation into avalanche paths, may lead to a corresponding upslope shift in avalanche runout zones. This process is most likely to be pronounced in coastal British Columbia, and particularly at or near the current tree line.

Changes in the timing and amounts of streamflow and cumulative watershed conditions will likely influence stream channel morphology and riparian function. Increased frequency of channel-forming peak flows is most likely in rain-dominated and hybrid systems. This could lead to channel instabilities, particularly in alluvial stream channels (e.g., Millar 2005). Changes to the return period of flood events also will have implications for engineering design criteria. In mountainous headwater stream systems, hillslope processes are coupled to stream channel processes such that changes in sediment delivery will affect sediment transport, channel morphology, and aquatic ecology (Benda et al. 2005). Similarly, changes in channel stability (i.e., bank erosion), windthrow, or landslides will likely affect supply and function of large woody debris (LWD) in streams (Hassan et al. 2005).

Potential changes in disturbance patterns at the watershed or landscape scales can also influence cumulative watershed effects. With warmer and drier summers projected for parts of British Columbia, fire seasons in these areas are expected to become longer with increased total area burned in each fire season (Flannigan et al. 2002, 2005). Wildfires can lead to widespread and severe surface erosion, debris flows, and flooding within watersheds (Curran et al. 2006). Severe impacts on stream channel morphology have been observed in response to changes in peak flow regime or increased sediment supply (Wondzell and King 2003), or related to loss of bank strength (Eaton et al. 2010). With increased fire activity, increases in erosion and flood processes can also be expected.

Widespread forest disturbances, such as insect infestations or disease, can also affect watershed processes. For example, changes in forest canopy structure in stands affected by the mountain pine beetle have resulted in changes to site-level hydrology. Across larger areas, this could lead to increased flood frequency–magnitude relationships (Hélie et al. 2005; Uunila et al. 2006). Increased frequency of flood events can influence channel morphology.

11 Miles, M. 2001. Effects of climate change on the frequency of slope instabilities in the Georgia Basin, B.C.: Phase 1. Natural Resources Canada, Canadian Climate Action Fund, Ottawa, Ont. Can. Climate Action Fund Proj. No. A160. Unpubl. report.

12 Ibid.

For example, Grainger and Bates (2010) examined increased flood risk attributed to the mountain pine beetle infestation and subsequent salvage harvesting in Chase Creek, and found that flood frequency increased by approximately 2.5 times. These changes resulted in significant channel changes and increased risks to private property and public infrastructure. Widespread tree mortality within riparian zones can affect the delivery of LWD to streams, riparian function, and instream dynamics of LWD (Everest and Reeves 2007). Riparian response to widespread forest disturbance, however, can be complex. For example, in beetle-affected stands near Vanderhoof, Rex et al. (2009) found that the dominance of unaffected spruce in the riparian areas of pine forests allowed for the maintenance of riparian function despite widespread pine mortality. Climate change is expected to affect ecological disturbance processes such as disease and insect outbreaks (Campbell et al. 2009), and therefore may also affect related riparian processes.

While fluvial geomorphic processes and disturbances are important for the renewal and diversity of fish habitat, altered rates and magnitudes of watershed processes above normal levels will have other implications for stream ecology and fish populations. Disturbances directly connected to stream channels, such as landslides and debris flows, can reduce the quantity and quality of fish habitats for several years or decades, and consequently the local abundance of salmon populations in affected stream reaches (Hartman and Scrivener 1990; Tschaplinski et al. 2004). Additionally, related processes such as local streambed scour can isolate the main stream channel from important seasonal fish habitats and refuges located in the floodplain, thus potentially reducing salmon survival and annual smolt production (Hartman and Scrivener 1990; Tschaplinski et al. 2004).

Changes in Water Quality

A considerable amount of research has focussed on the potential effects of climate change on water supplies; however, relatively little is known about the related effects on chemical water quality. Recent IPCC publications provided only cursory details on the effects of climate change on water quality (Kundzewicz et al. 2007; Bates et al. 2008). Limited predictions in this area may be partly related to the challenge of separating the potential effects of climate change on water quality from those of land and water use on surface and ground waters. Nevertheless, interest in this topic is growing (Whitehead et al. 2009).

The effects of climate change on chemical water quality are likely complex and will vary with the physical, geographical, and biological characteristics of each watershed. Changes in climatic conditions have the potential to either mitigate or worsen existing water quality issues, especially when combined with the effects of natural resource use (Dale 1997). The most important factors that influence the effects of climate change on water quality are increases in atmospheric and water temperatures and changes in the timing and amount of streamflow.

Changes in stream or lake temperatures and effects on fish

Climate change has the potential for both direct and indirect effects on stream temperature. Most directly, the energy exchanges that govern stream temperature may change. Solar radiation, generally the dominant driver of daily maximum temperatures, depends on the Sun's position in the sky and the transmissivity of the atmosphere (a function of humidity, cloud cover, dust content, and other factors), and is therefore not directly related to air temperature; however, incident solar radiation will be influenced by any changes in cloudiness that accompany climate change. Incident longwave radiation, which acts to suppress nighttime cooling, increases with increasing air temperature and also with increasing cloud cover, and thus should be influenced by climate warming. Groundwater is typically cooler than stream water in summer during daytime and warmer during winter, and thus acts to moderate seasonal and diurnal stream temperature variations (Webb and Zhang 1997; Bogan et al. 2003). Deep groundwater temperatures tend to be within about 3° C of mean annual air temperature (Todd 1980). It is reasonable, therefore, to assume that climate-induced groundwater warming will influence stream temperature regimes, particularly during base-flow periods when groundwater is a dominant contributor to streamflow and especially when energy inputs at the stream surface are relatively minor (e.g., at night).

Projected hydrologic changes in some areas may produce lower streamflow in late summer, and also less groundwater discharge. Both of these influences could promote higher late-summer water temperatures. Similarly, reductions in late-summer streamflow associated with glacier retreat are expected to result in higher stream temperatures (Moore et al. 2009).

Less directly, climate change may result in changes to vegetation and (or) land use patterns, which could influence stream shading and possibly channel morphology. For example, it is generally accepted that the area burned by wildfires will increase in some areas under a future warming climate (Flannigan et al. 2005). Debris flows often increase in frequency following wildfire, and can generate increased stream temperatures by producing wider channels (which reduces shading) and removing substrate. This decreases the potential for hyporheic exchange, which can moderate stream temperatures (Johnson 2004). Where wildfires burn through riparian zones, the reduction in canopy shade can produce higher stream temperatures caused by increased insolation (Leach and Moore 2010) and also cause channel widening due to loss of bank strength (Eaton et al. 2010). Dunham et al. (2007), working in the Boise River basin in Idaho, found that streams in undisturbed catchments were cooler than streams subject to riparian wildfire, which in turn were cooler than streams that experienced channel disturbance in addition to riparian wildfire.

Other indirect influences may occur through human-induced changes in drainage patterns to address changing patterns of water availability and scarcity. For example, withdrawals of water for irrigation or other uses typically cause increased stream temperatures (e.g., Hockey et al. 1982), whereas the effects of impoundments are more complex, depending on the depth of the reservoir and the depth from which downstream flow releases originate (e.g., Webb and Walling 1997).

Most attempts to evaluate potential stream temperature responses to climate change have used the statistical relationship between stream temperature and air temperature to assess sensitivity related to the projected changes in air temperature derived from GCM output (e.g., Eaton and Scheller 1996; Mohseni et al. 1999; Morrill et al. 2005). Morrison et al. (2002) conducted a more comprehensive assessment for the Fraser River. They used a conceptual model of catchment hydrology (the University of British Columbia Watershed Model), in conjunction with projections of future temperature and precipitation, to generate scenarios for streamflow for sub-basins of the Fraser River. They then used these climate and streamflow projections, together with a model of energy exchanges and water flow in the Fraser River stream network, to simulate stream temperatures. The scenarios suggest an increase in the spatial and temporal frequency of temperatures exceeding 20° C, particularly below the confluence with the Thompson River.

Stream and lake temperatures are projected to increase with climate change, which will result in several specific concerns for aquatic and fish species including salmon (Levy 1992; Mote et al. 2003). Increased water temperatures could affect metabolic rates and increase biological activity and decomposition. In aquatic systems with sufficient nutrient and oxygen supplies, an increase in biological productivity can increase nutrient cycling and possibly accelerate eutrophication (Murdoch et al. 2000). However, it is likely that in aquatic systems currently stressed by high biological oxygen demand any subsequent increase in water temperatures could decrease biological productivity as a result of a decline in the oxygen-holding capacity of the water.

The vulnerability of fish to climate change will partly depend on how much the water body warms and the sensitivity of individual fish species to temperature and habitat changes. Temperature-related risks for fish include both acute (short-term) and chronic (also termed "sublethal" or "cumulative") effects.[13] The vulnerability of fish may depend on local-scale watershed management strategies, which have the potential to exacerbate or mitigate the effects of climate change. For example, research on the Little Campbell River (a tributary entering Boundary Bay, about 35 km south of Vancouver) concluded that watershed remediation or degradation can greatly affect the ultimate impacts of climatic change on chronic thermal risks to fish.[14]

Responses to increased water temperatures will generally be defined by fish species or specific stocks, and how these changes will affect the various life stages (from egg to spawning adult). Nelitz et al. (2007) provided a useful species and life-stage-

13 Fleming, S.W. and E.J. Quilty. 2006. A novel approach: reconnaissance analysis of the Little Campbell River watershed. Report prepared for Environmental Environ. Qual. Sect., Lower Mainland Reg., B.C. Ministry of Environment. Aquatic Informatics Inc., Vancouver., B.C. Unpubl. report. www.env.gov.bc.ca/epd/regions/lower_mainland/water_quality/reports/ltl-campbell-riv/pdf/ltl-camp-riv-analysis.pdf (Accessed May 2010).

14 Ibid.

specific summary of potential biological vulnerabilities to climate-induced changes in water flows and temperatures. Increased temperatures in temperature-sensitive systems may result in increased frequencies of disease, increased energy expenditures, altered growth, thermal barriers to both adult and juvenile migration, delayed spawning, reduced spawner survival, altered egg and juvenile development, changes in biological productivity and other rearing conditions, and altered species distribution.

Changes in baseline conditions of aquatic ecosystems could also influence the outcomes of competition between species with differential temperature tolerances, as well as affect the necessary habitat requirements and survivability of sensitive species (Schindler 2001). Watersheds with warm water temperatures or low flows that currently affect salmonid survival are centred in the southwest, southern Interior, and central Interior of British Columbia (Nelitz et al. 2007). Under a changing climate, it is projected these areas will be further stressed. Salmonids show species-specific thermal optima and tolerances (Selong et al. 2001; Bear et al. 2007), and even small (1–2° C) differences in these conditions may result in marked differences in species distribution (Fausch et al. 1994). Distribution changes may be the direct result of the effects of water temperature on fish physiology, or (indirectly) a consequence of displacement of temperature-sensitive species such as bull trout (*Salvelinus confluentus*) by competing species such as rainbow trout (*Oncorhynchus mykiss*). Therefore, shifts in population distributions may be unavoidable and likely will result in the loss of salmonids in some areas where habitat conditions are currently close to tolerable limits (Nelitz et al. 2007). The effects of increased water temperatures are likely compounded wherever hydrologic regime changes reduce seasonal flows. For example, the limits of fish distribution in headwater areas are further altered by changes in the abundance and distribution of perennial, intermittent, and ephemeral watercourses.

Alternatively, in regions or specific water bodies where temperatures are below thermal optima for fish or temperature sensitivity is not a concern, increased water temperatures may promote fish growth and survival. Even minor temperature increments can change egg hatch dates and increase seasonal growth and instream survival in juvenile salmon. At Carnation Creek, minor changes in stream temperatures in the fall and winter due to forest harvesting profoundly affected salmonid populations, accelerating egg and alevin development rates, emergence timing, seasonal growth, and the timing of seaward migration (Tschaplinski et al. 2004).

The combination of increased temperatures and decreased late-summer base flows (low flows) could increase the stress for fish and other aquatic biota in the future. Low flows can cause a reduction in habitat availability, food production, and water quality, and can heighten the effects of ice on smaller streams during the winter time (Bradford and Heinonen 2008).

Changes in chemical water quality processes

Water quality changes related to temperature effects on terrestrial ecosystems are also possible. For example, increases in air temperature can increase soil productivity and rates of biogeochemical cycling, which may influence the chemical composition of runoff from terrestrial ecosystems. Soil microbes play an important role in influencing nitrogen retention and release to surface waters in forested watersheds (Fenn et al. 1998). Specifically, nitrification rates in soils are generally temperature-dependent; thus, nitrate concentrations in stream water are highly correlated with average annual air temperature (Murdoch et al. 1998) and future projected temperature changes.

Another important climate change factor that may change the rates of nutrient cycling in watersheds is the projected shifts in tree species composition related to temperature changes. This is because different tree species have different nutrient cycling regimes. Similarly, increases in other climate-related disturbances, such as wildfire or forest pest infestations, have the potential to increase nutrient cycling and leaching of mobile nutrients (e.g., nitrate) to surface waters (Eshleman et al. 1988). The effects of these disturbances are discussed in Chapter 12, "Water Quality and Forest Management."

One of the most direct effects of a changing climate on water quality is linked to changes in the timing and volume of streamflow. For example, as streamflows decline, the capacity of freshwaters to dilute chemical loadings will be reduced (Schindler 2001). Where the greatest temperature increases are projected during the summer and declines in surface water volumes are likely (i.e., the Columbia Basin and the Okanagan), water quality deterioration is possible as biologically conservative nutrients and contaminants could become more concentrated.

Where precipitation is expected to decline (i.e., southern and central British Columbia), deteriorating water quality will become a greater issue than in regions experiencing only an increase in air temperature. The key issue in these regions will be the decreased dilution capacity (higher pollutant concentrations) related to altered flows. Declines in surface water flows result in longer resident times for chemicals entering lakes (Whitehead et al. 2009). This is of greatest importance for biologically reactive chemicals for which longer resident times can result in increased biological reaction and increased potential for eutrophication (Schindler 2001).

Some of the effects we have described here may be mitigated in regions such as the Peace Basin and northwest British Columbia, where increases in summer precipitation and an overall wetter climate are predicted. For example, increased flows may potentially result in increased dilution of some nutrient contaminants, offsetting the effects of temperature increases and the associated evaporative demand. In some instances, greater dilution of pollutants may actually result in a positive effect on water quality. Similarly, an increase in the dilution capacity of streams may occur during the spring freshet in regions with predicted increases in winter precipitation. However, a counterbalancing effect may become evident on any water quality improvements because of an increase in stream power and non-point source pollutant loadings to watercourses. Higher runoff can lead to an increase in erosion and sediment transport in aquatic systems and reduced residence times, resulting in a decrease in chemical and biological transformations. This is of greatest concern for nutrients and chemicals that tend to adsorb to suspended solids, such as phosphorus and heavy metals. Higher concentrations of phosphorus, along with warmer temperatures, can promote algal blooms that reduce water quality (Schindler et al. 2008).

MODELLING REQUIREMENTS FOR CLIMATE CHANGE APPLICATIONS AT THE FOREST MANAGEMENT SCALE

Because of the uncertainty associated with the prediction of local climate change using climate models, natural resource managers must consider the effects of drier, wetter, more variable, less variable, or simply warmer conditions depending on the interactions of several site-specific environmental factors. Given the uncertainty of future climate projections at a regional level, as well as the incremental effects of various land uses on watershed processes, watershed-scale hydrologic models possess the potential to address short- and long-term forest management questions. These analyses may include problems such as an assessment of possible future growing conditions, the permanence of wetlands and small streams, or the potential changes to flooding, low flows, and other disturbances as a result of a changing climate. Yet, as a recent review of hydrologic models points out, numerous challenges are likely related to the inherent limitations of these models and the data inadequacies that exist across British Columbia (Beckers et al. 2009c).

In this section we highlight the specific qualities required in a hydrologic model *for climate change applications at the forest management scale*, and discuss several of the suggested improvements for climate change or forest management applications. Much of this information is summarized from Beckers et al. (2009a, 2009b), who provided a detailed review of several currently available hydrologic models and the suitability of these models for applications related to climate change. For a general discussion of weaknesses and limitations of using numerical models and other methods for detecting and predicting changes in watersheds, the reader is directed to Beckers et al. (2009a, 2009b, 2009c), and Chapter 16, "Detecting and Predicting Changes in Watersheds."

The suitability of any model depends on several components, such as available data and resources, and the ultimate end use of the modelled results. The presence of these components in selected watershed models will enable the simulation and investigation in a climate change context. Table 19.4 summarizes these critical components.

TABLE 19.4 *Climate change hydrologic model components (adapted from Beckers et al. 2009c)*

Modelled output	Required model component
Atmospheric evaporative demand	Solar radiation, humidity, and wind speed
Evaporation and precipitation interception	Leaf area index Stomatal resistance Forest growth (productivity) Forest survival (mortality) Temporal input control
Snow accumulation and melt	Physical or analytical snowmelt equations Rain-on-snow simulation
Permafrost, river ice, and lake ice	Frozen soil influence on water movement River and lake ice model component
Glacier mass balance adjustments	Glacier accumulation or melt model Glacier geometric response
Streamflow	Groundwater Lakes Wetlands Water consumption (water supply systems)
Stream and lake temperatures	Water temperature model component
Frequency and magnitude of disturbances	Channel routing (floods) Multiple vegetation layers (wildfires, pests) Vegetation albedo, radiation transmissivity (wildfires, pests) Soil albedo (wildfires) Hydrophobicity (wildfires) Landslide simulation

Downscaling for Watershed Modelling

Projected changes to climate are available at scales of greater than 10 000 km^2, whereas watersheds of interest generally range from 5–500 km^2 in size. Linking large-scale global climate model projections to hydrologic models requires downscaling of climatic data. The downscaling method will depend on the hydrologic model used and the nature of the question to which the model is applied. Statistical methods are most common, as these are computationally less intensive than dynamical methods. These methods range from the bias correction spatial downscaling techniques designed for use with gridded models to draw on monthly GCM data (Wood et al. 2002; Widmann et al. 2003; Salathé 2005), to more sophisticated applications such as hybrid methods that use daily information from GCMs and draw on the strengths of statistical tools and stochastic weather generators. Dynamic downscaling results from regional climate models (RCMs) are being produced at higher resolution over British Columbia (approximately 15 km^2), and multiple RCMs have been compared over North America via the North America Regional Climate Change Assessment Program. The Pacific Climate Impacts Consortium is developing methods that apply statistical downscaling to dynamically downscaled projections to provide higher temporal and spatially resolved information similar to approaches applied outside of Canada (e.g., Bürger 2002).

Global Climate Model Selection for Watershed Modelling

Modelling future changes requires a clear rationale for GCM selection. The GCMs selected will dictate the range and median of future projected changes (Pierce et al. 2009). For example, the range in projections for the 2050s depends more on the choice of models than on emissions scenarios (Rodenhuis et al. 2007). To reduce computational time, remove outliers, and ease interpretation of results, Hamlet et al.[15] have selected a subset of the GCMs; however, a clear consensus on how to evaluate model performance and select outliers does not currently exist. Overland and Wang (2007) identified and eliminated outliers by comparing historical GCMs to observational data, whereas Manning et al. (2009) weighted less biased models more greatly to create a probabilistic ensemble. A carefully selected subset will likely represent the range of possible wet-dry and warm-cool futures to present an adequate characterization of the related uncertainty. In British Columbia, knowledge of GCM model selection is currently expanding. The Pacific Climate Impacts Consortium expects to publish foundation papers and a guidance report on this topic in 2010. For more information, go to: http://pacificclimate.org/.

Modelling Atmospheric Evaporative Demand

Increases in atmospheric evaporative demand may lead to greater evaporative losses from water bodies and changing water demands of vegetation. Incorporating weather variables into calculations of reference evapotranspiration is therefore critical. Subsequently, physically based approaches to calculating evapotranspiration should provide the greatest level of confidence in results. Because empirical methods are based on historical data, physically based equations are better suited for predicting possible shifts in hydrologic responses outside historical data ranges. Many of the models reviewed by Beckers et al. (2009c) employ the Penman-Monteith equation recommended by the Food and Agricultural Organization of the United Nations and the American Society of Civil Engineers to determine reference evapotranspiration (Allen et al. 2005).

Although the theoretical understanding of suitable equations to calculate reference evaporation is advanced, the main challenge in anticipating future increases in evaporative demand arises from a lack of understanding regarding possible changes in temperature, solar radiation, humidity, and wind speed. Projections of future climate change have focussed primarily on analyzing and downscaling mean temperature and precipitation outputs from GCMs. Relatively little research has been done to extract and analyze the remaining variables, or to find adequate methods for downscaling modelled output into formats suitable for use in hydrologic models, to points (representative of meteorological stations), or to high-resolution grids. Thus, we need to develop improved methods of downscaling solar radiation, humidity, and wind speed from GCMs to drive hydrologic models.

Modelling Future Evaporation and Precipitation Interception

To apply hydrologic models for planning purposes, we must consider the issues surrounding forest growth and mortality. When conducting long-term model simulations, it may be important to determine whether the model input is easily adapted to represent gradual or abrupt changes in vegetation disturbance. The ability to vary vegetation properties over time within a single model simulation (i.e., the ability to change properties without having to re-start the model) is referred to as "temporal input control" (Table 19.4).

The amount and type of vegetation and its physiological characteristics have an important effect on site water balance. The interaction between vegetation and the atmosphere (i.e., evapotranspiration, precipitation interception) is determined by vegetation surface area (Monteith and Unsworth 1990; Shuttleworth 1993), typically represented as leaf area index (LAI) in most hydrologic models. Leaf area index is also a primary reference parameter for plant growth. Thus, within a climate change context, explicit representation of vegetation (i.e., LAI) is a critical model parameter to describe forest characteristics, and potential effects of episodic or long-term changes.

Stomatal resistance (or its inverse, stomatal conductance) is another crucial parameter (see Table 19.4) used to calculate the vegetation transpiration rate from humidity (vapour pressure) gradients (Monteith and Unsworth 1990). Stomatal resistances vary between plant species and are an important physiological model parameter. Hydrologic models need to simulate the closing of stomata (i.e., an increase in stomatal resistance) when atmospheric water demand exceeds water availability (i.e., to describe plant response to atmospheric and soil drying). Therefore, inclusion of multi-layered vegetation and associated vegetation parameters can be an important quality for a hydrologic model to pos-

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sess. To improve the ability of hydrologic models to simulate the hydrologic effects of altered vegetation composition, suggested model improvements include adapting watershed models to include forest growth and mortality, linking to existing forest growth and mortality models, and (or) adding temporal input control to some models.

Modelling Future Snow Accumulation and Accelerated Melt

For long-term simulations of climate change, a key challenge is the ability of a hydrologic model to spatially simulate both snow accumulation and snowmelt processes. Over a single model run, these models must also be able to initially represent predominantly nival conditions that then become hybrid (mixed) conditions or even pluvial (Beckers et al. 2009c). Additionally, changes in the form of precipitation (rain or snow) in the late fall or early spring may become increasingly important factors to simulate. As such, the ability of hydrologic models to accurately model mixed regimes (i.e., rain-on-snow energy transfer) can be crucial. Snowpack accumulation and melt is also an important factor for other water balance components, as these processes relate to albedo and snow-covered versus bare ground. Where models do not accurately model the spatial extent of snow, errors can occur in estimating snowmelt contributions to streamflow or in predicting the onset or rate of evapotranspiration. Model testing approaches (e.g., Jost et al. 2009) that incorporate SWE data measurements from a range of elevations and aspects hold promise in helping to validate model output in mountainous, data-sparse watersheds. Models with physically based or analytical (temperature-radiation) snowmelt routines are better suited than empirical models to predict the potential for accelerated melt under a changing climate (Table 19.4) for the same reasons mentioned previously.

Modelling Soil Freezing, Permafrost, Lake Ice, and River Ice

River and lake ice formation and break-up processes are often the focus of specialized kinematic models (e.g., Beltaos 2007) that are not typically incorporated into watershed-scale hydrologic models used in forest management applications. Soil temperatures, however, are more widely accounted for in watershed models, typically to calculate the ground heat flux component of the snowpack energy balance (e.g., Wigmosta et al. 1994). Only the Cold Regions Hydrological Model (Pomeroy et al. 2007) has the ability to assess frozen soil conditions (via soil temperatures) and associated effects on water movement among the models reviewed by Beckers et al. (2009c). The following general modelling improvements are therefore suggested.

- Increase the ability of hydrologic models to simulate the effects of permafrost thaw on hydrological processes applicable to the northern portions of British Columbia, Alberta, and other areas where permafrost occurs. Frozen soil conditions may also be important to model in non-permafrost areas (e.g., effects on infiltration).
- Improve our understanding of how climate change will alter the three-way interaction between streamflow generation, water temperatures, and river and lake ice formation and break-up.
- Develop tools that allow resource managers to assess the importance of these interactions (and how they may change in the future) for forest management.

Modelling Glacier Mass Balance

For some watersheds, the ability to simulate changes in glacial melt contributions to streamflow may be critically important. Glacial processes are represented in some models that simulate the increased melt rates related to climate change (Beckers et al. 2009c); however, for long-term simulations, it is also necessary to calculate glacier mass balance and to adjust glacier area and volume (i.e., to simulate glacial retreat) . Two important components are the capacity to: (1) track glacier mass balance, and (2) account for glacier geometric response to mass balance. This latter function was built into a version of HBV-EC (Stahl et al. 2008) by drawing on the concept of volume-area scaling. The Western Canadian Cryospheric Network is currently working on a model suite that will project glacier response using a physically based glacier dynamics model, which will then be used in parallel with a hydrologic model to generate scenarios. Alternatively, stand-alone models of glacier mass balance can be used to estimate future glacier volume, which will become an input to hydrologic models with glacier processes.

Modelling Future Stream Temperatures

Models to predict stream temperatures fall into two general classes (Sridhar et al. 2004): (1) empirical relationships based on observations of stream temperature and stream properties (such as discharge, channel geometry, and streamside vegetation characteristics); and (2) models that represent the energy balance of the stream. Recently, the use of physically based models to predict stream temperature has become feasible by interfacing with GIS methods. Although numerous models have been developed to predict stream temperature (Webb et al. 2008), none of the hydrologic models reviewed by Beckers et al. (2009a, 2009c) possessed this capability inherently. At a larger scale and as mentioned above in "Changes in stream and lake temperatures and effects on fish," Morrison et al. (2002) conducted a comprehensive assessment using the University of British Columbia Watershed Model, in conjunction with projections of future temperature and precipitation, to generate streamflow scenarios for sub-basins of the Fraser River. Other temperature models are used operationally in British Columbia, such as the FJQHW97 river temperature model. The federal Department of Fisheries and Oceans has used this model for the Fraser River during the salmon migration period and it has played an important role in aiding decisions to open or close commercial fisheries (Foreman et al. 2001). This model was also used for climate change analysis (Foreman et al. 2001).

To improve future stream temperature simulations, existing watershed models could be adapted to spatially simulate stream temperatures or couple to existing aquatic (e.g., salmonid) habitat simulation models. However, where surface water–groundwater interactions are strong controls on stream temperature, fully coupled models that include subsurface processes at a relevant scale would be necessary.

Modelling the Future Frequency or Magnitude of Forest Disturbances

Watershed modelling can be used to assess the suitability of current infrastructure (e.g., stream crossings) under potential future climate conditions, and (or) to determine the suitability of engineering design criteria using scenarios. In some rain-dominated regimes, the ability of watershed models to examine such questions may depend on the accurate simulation of preferential runoff mechanisms (e.g., Carnation Creek on Vancouver Island; Beckers and Alila 2004). In snow or mixed regimes, accurate simulation of melt rates is important for predicting peak flows (e.g., Redfish Creek in southeast British Columbia; Schnorbus and Alila 2004).

Other disturbances that are projected to increase include wildfire, forest pests (insects), windthrow, breakage of trees, and landslides. Of these disturbances, the modelling of landslides provides a clear synergy with watershed simulation (Table 19.4). Landslide modelling has been the focus of specialized physically based models, such as the distributed Shallow Landslide Analysis Model (dSLAM; Wu and Sidle 1995) and the Integrated Dynamic Slope Stability Model (IDSSM; Dhakal and Sidle 2003), and has been incorporated in the Distributed Hydrology Soil Vegetation Model (DHSVM; Doten et al. 2006).

In contrast, specialized windthrow models (e.g., Lanquaye and Mitchell 2005) currently offer minimal synergies with watershed modelling. This lack of synergy also holds true for predicting the occurrence of pests. It is critically important, however, for hydrologic models to incorporate (as inputs) the changes in physical watershed characteristics that may occur as a result of these disturbances. For example, an important aspect related to tree mortality is the change in canopy albedo and solar radiation transmissivity (Table 19.4), which in turn affects the radiation energy balance of affected stands.

Forest fires also cause vegetation changes that, depending on fire behaviour, may include either removal of the understorey without canopy disruption or full combustion of the overstorey, resulting in standing dead timber. These complex changes can be represented in a straightforward fashion only with models that allow for multiple (stratified) vegetation layers (Table 19.4). Fires can also cause changes in soil properties that affect the hydrologic response, including altered soil albedo, and (under certain conditions) the formation of hydrophobic conditions, which limit soil infiltration (Agee 1993). Although soil hydrophobicity is known to decline over time, the overall process is poorly understood (DeBano 2000) and, as such, the ability to simulate these conditions is challenging. For example, although it is possible to alter soil physical properties in existing hydrologic models, representing the potential effect of soil hydrophobicity on infiltration is problematic because no models allow temporary changes to soil properties within a single model run to account for a reduction in hydrophobicity over time (Beckers et al. 2009c).

The current understanding of climate change influences on average meteorological conditions is much further developed than that of understanding potential changes in the frequency and magnitude of extreme events (Rodenhuis et al. 2007). An improved understanding of extreme events (temperature, precipitation, and wind) under a changing climate is needed to advance hydrologic modelling. An increased ability to use models to investigate potential forest disturbances such as landslides, fire hazards, pests (insects), and windthrow is also needed. The outputs from these models could then be used to parameterize hydrologic models for forest management purposes.

Modelling Future Streamflow

Most currently available watershed models will calculate changes in streamflow, infiltration, soil moisture conditions and shallow subsurface runoff, and the subsequent discharge of water to the stream channels without applying any modifications to the model. Nonetheless, specific questions regarding the interaction of forest management and climate change may create difficulties for existing models in certain settings. For example, changes in groundwater recharge rates associated with climate change (e.g., Scibek and Allen 2006a, 2006b) may have consequences for base flow contributions to low flows. The capability to account for the anticipated increased competition between human use and instream needs may be another important feature in selecting a model (Table 19.4).

Improvements in simulating altered peak and low flows in a changing climate are often contingent on advances in the previously discussed topic areas (evapotranspiration, snow accumulation and melt, permafrost and river and lake ice processes, glacier mass balance adjustments, etc.). Furthermore, if a model was developed and calibrated to simulate snowmelt-dominated watershed conditions and is subsequently used to assess the consequences of a regime shift to mixed or rainfall-dominated regimes, its accuracy in predicting future streamflow conditions may be reduced. Additional model improvements include processes related to groundwater, wetland and lakes, and other factors such as human water consumption (water competition) that affect streamflow. This capability is currently limited in those models reviewed by Beckers et al. (2009a, 2009c).

The watershed models reviewed by Beckers et al. (2009c) had varying capabilities for examining climate change questions; however, incremental enhancements to existing models (rather than the development of new models) will help guide forest management decisions. For instance, to apply the complex, physically based models better suited to addressing climate change questions, further efforts are required to enhance and organize data resources. Examples include producing spatially coherent vegetation data sets with up-to-date LAI and stomatal resistance information, and incorporating weather variables such as solar radiation, humidity, and wind speed into climate change projections. A fundamental barrier to considering climate change in a forest management context is the uncertainty in possible future climates (and emissions), with current projections offering a wide range of possible outcome scenarios.

SUMMARY

British Columbia's climate has changed over the last 100 years and will continue to experience change with the future looking warmer and wetter. Transformation of local air temperature and precipitation regimes will drive changes in groundwater and the magnitude and timing of both low and high streamflows in any given watershed. Many areas will see accelerated snowmelt and increased water levels in the winter. Projected warming coupled with altered streamflows will likely increase stream temperatures affecting water quality and, consequently, fish in many areas. Glaciers and permafrost will to continue to melt, and landslide regimes will ultimately respond to all of these drivers. The associated effects will have many important implications for the fisheries, agriculture, forestry, recreation, hydroelectric power, and water resource sectors. As this chapter has illustrated, the effects at a local scale will be complex and vary in importance according to the sensitivity of local watersheds conditions to climatic changes.

Currently, practical management responses to climate change are not well formalized, as the focus of the past few years has largely been on projecting and understanding what the future might hold. As a next step, the development of effective climate change management responses will likely involve local-level strategies that result in both short- and long-term benefits to ecosystems and society beyond climate change applications. The selection of such a suite of approaches may be the best chance to ensure the effective stewardship of watershed resources and associated values in the future.

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Ablation "The process by which ice and snow waste away as a result of melting," evaporation and (or) sublimation. (1):1 quote[1]

Absorption "The taking up, assimilation, or incorporation of molecules, ions, or energy into the interior of a solid or liquid." *Compare to adsorption.* (2):709 quote

Accuracy "Closeness of computations, estimates or measurements to the exact or true values." (31):6 quote

Acidosis "A condition in which body fluids become more acidic, i.e. the pH is less than 7.4, and the capacity of the body to buffer hydrogen ions is diminished." *Compare to alkalosis.* (35) quote

Active Floodplain Lowlands bordering a river, which are subject to flooding on a periodic basis. Floodplains are composed of alluvium deposited on land during flooding. The active area is characterized by recently deposited river-borne debris, limited terrestrial vegetation, and recent scarring of trees by material transported by floodwaters. (3):Section A paraphrase

Acute Toxicity "Toxic or poisonous effect that occurs during or soon after exposure to a toxicant. The term usually refers to a lethal effect (death) or to a major sub-lethal effect such as greatly altered behaviour or physiology. Formal acute toxicity tests establish the concentration of a substance that kills a specified fraction of the test organisms (usually 50%) within a specified time (usually 96 hours or less)." *Compare to chronic toxicity.* (2):709 quote

Adfluvial "Migrating between lakes and rivers or streams." (2):709 quote

Adsorption "Physical adhesion of molecules of gases, liquids, or dissolved substances to the surfaces of solids or liquids with which they are in contact." *Compare to absorption.* (2):709 quote

Advection The transfer of heat, cold, humidity, solutes, pollutants, or other properties by the horizontal movement of an air mass or water current. *Compare to convection.* (28) pers. comm.

Aerodynamic Resistance "The bulk meteorological descriptor of the role of the atmospheric turbulence in the evaporation process." It depends on wind speed, surface roughness, and atmospheric stability. (34):107 quote, paraphrase

Affluent (Stream) A branch or tributary stream that flows into a larger stream channel. (1):5 paraphrase

Aggradation "The geologic process by which streambeds, floodplains and the bottoms of other water bodies are raised in elevation by the deposition of material eroded and transported from other areas. It is the opposite of degradation." (4):G-1 quote

Albedo "The ratio of reflected to incident radiation." Albedo depends on surface properties such as colour and texture, which influence the absorption rate and angle of solar incidence, respectively. "Freshly fallen snow, for example, reflects more solar radiation back into the atmosphere than grass or forest," indicated by its higher albedo. (5):Section A quote; (6):297 paraphrase; (6):297 quote

Alevin "Larval salmonid that has hatched but has not fully absorbed its yolk sac, and generally has not yet emerged from the spawning gravel." (2):709 quote

Alkalosis "A condition in which the body fluids become more alkaline, i.e., the pH is more than 7.4." *Compare to acidosis.* (35) quote

Allochthonous Material "Derived from outside a system, such as leaves of terrestrial plants that fall into a stream." *Compare to autochthonous material.* (2):710 quote

1 Citations indicate reference as numbered in list of references following glossary, page number, and whether the definition has been quoted or paraphrased; for example, "(1):1 quote" indicates a quote from page 1 of reference 1. Pers. comm. indicates definitions generated by the compilers of this glossary.

Allogenic "Exogenous, caused by external factors, such as a change in habitat or environment caused by flooding." *Compare to autogenic.* (1):8 quote

Alluvial "Deposited by running water." (2):710 quote

Alluvial Fan "A relatively flat to gently sloping landform composed of predominantly coarse grained soils, shaped like an open fan or a segment of a cone, deposited by a stream where it flows from a narrow mountain valley onto a plain or broad valley, or wherever the stream gradient suddenly decreases." (7):D.1 quote

Alluvium Sediment transported and deposited by flowing water. Particle size distribution of deposits depends on water energy, which varies with channel gradient, lateral distance from stream, or presence of flow obstacles, resulting in deposits that tend to be sorted or stratified into components (e.g., gravels, sands, silts, clays). (1):8 paraphrase; (6):297 paraphrase; (8):10, 11 paraphrase

Anabranch "A channel that branches off from a river, re-joining it further downstream." (9):Glossary terms quote

Anadromous "Fish that breed in freshwater but live their adult life in the sea. On the Pacific coast, anadromous fish include all the Pacific salmon, steelhead trout, some cutthroat trout and Dolly Varden char, lampreys and eulachons." (4):G-1 quote

Anaerobic "Characterizing organisms able to live and grow only where there is no air or free oxygen, and/or conditions that exist only in the absence of air or free oxygen." (1):10 quote

Anastomosing "The branching and rejoining of channels to form a netlike pattern." (1):11 quote

Anisotropic Medium "Denoting a medium in which certain physical properties are different in different directions. An example would be hydraulic conductivity that differs between the vertical and lateral directions due to layering and alignment of soil grains." (12) quote

Annual Flood "The highest peak discharge of a stream in a water year." *See flood.* (1):11 quote

Antecedent Moisture "The amount of moisture already present in the soil before a specified rainstorm." (38) quote

Aquifer A saturated permeable subsurface layer such as sand, gravel, sandstone, or limestone that stores or transmits groundwater. "Use of the term is usually restricted to those water-bearing structures capable of yielding water in sufficient quantity to constitute a usable supply." (2):710 paraphrase; (1):14 quote

Aquitard A poorly permeable subsurface layer that impedes groundwater movement and does not yield water freely to wells. (1):15 paraphrase

Armour To protect erodible areas by covering with erosion-resistance materials such as rock or concrete. (1):16 paraphrase

Assart Period The period during which land is cleared of trees and forest understorey. (36) paraphrase

Autochthonous Material Material derived within a system, such as organic matter produced instream. Includes primary producers as well as aquatic biota such as invertebrates and fishes. *Compare to allochthonous material.* (2):710 paraphrase

Autogenic "Relating to or caused by a change in the environment or an individual organism due to some endogenous factor, i.e., one that comes from within the environment or organism." *Compare to allogenic.* (35) quote

Avulsion "An abrupt change in the course of a stream whereby the stream leaves its old channel for a new one." (7):D.1 quote

Backscarp *See escarpment.*

Backwater Effect Upstream increase in water level produced when a barrier such as a dam or downstream flooding obstructs flow. (7):D.1 paraphrase

Bankfull (Stage) Water surface elevation at which a stream first overflows its natural banks, spilling water onto the floodplain. (10):17 paraphrase

Basal Area "The area of the circle formed by the cross-section of a tree taken 1.3 m above the ground." (3):6 quote

Basal Till "The till that is transported at, or deposited from, the bottom of a glacier." (37) quote

Base Flow Streamflow coming from sustained subsurface sources, not directly from surface runoff. (1):24 paraphrase

Basin "A geographic area drained by a single major stream; consists of a drainage system comprised of streams and often natural or man-made lakes." *Also referred to as Drainage Basin; see catchment area, watershed.* (1):25 quote

Basin-lag A characteristic of a basin that describes the interval between a precipitation event and the time when the peak flow occurs at the basin outlet. (38) paraphrase

Bedload Sediment particles transported on or near the streambed by rolling and bouncing. (3):Section B paraphrase

Benthic "Occurring at the base of bodies of water: lakes, oceans, and seas." (38) quote

Benthos "Animals and plants living on or within the substrate of a water body." (2):711 quote

Bifurcation The division of a stream channel into two branches or a fork in the stream channel. (11) pers. comm.

Bioassay Assessment of a substance (e.g., water sample) by testing its effect on the growth of an organism under controlled conditions and comparing the result with an agreed standard. (2):712 paraphrase; (5):Section B paraphrase

Biofilm "A colony of bacteria and other microorganisms that adheres to a substrate and is enclosed and protected by secreted slime . . . They are important components of aquatic and terrestrial ecosystems, typically providing nutrients for small organisms at the base of food chains." (35) quote

Biological Oxygen Demand "Amount of molecular oxygen that can be taken up by nonliving organic matter as it decomposes by aerobic biochemical action." (2):712 quote

Bioturbation "The disruption of sediment by organisms, seen either as a complete churning of the sediment that has destroyed depositional sedimentary structures, or in the form of discrete and clearly recognizable burrows, trails, and traces." (39) quote

Bog A peat landform characterized by: a dense layer of peat; acidic conditions; low nutrient content; water table at or near the surface; usually covered with mosses, shrubs, and sedges; and trees possibly present. *Compare to fen, marsh, swamp, shallow waters.* (32) paraphrase

Boundary Layer "The layer of reduced velocity in fluids, such as air and water, that is immediately adjacent to the surface of a solid past which the fluid is flowing." (1):37 quote

Braided Stream Stream that forms a "network of branching and recombining channels separated by … islands or channel bars." (2):712 quote

Bryophyte "A nonvascular plant belonging to the division *Bryophyta*. Some include mosses, liverworts, and hornworts in this division, but most scientists now only include mosses, consigning the liverworts to the division *Hepatophyta* and hornworts to the division *Anthocerotophyta*." (36) quote

Buffer Strip Riparian area adjacent to streams or lakes left intact as a protective barrier. (2):712 paraphrase

Bulk Density "Mass of an oven-dry soil sample per unit gross volume (including pore space)." (31):23 quote

Canopy "The more or less continuous cover of branches and foliage formed collectively by the crowns of adjacent trees." (3):11 quote

Capillary Fringe (Zone) "The part of the vadose zone that lies just above the water table, where water can be drawn upward by capillary forces." (30):553 quote

Cascade "A short, steep drop in stream bed elevation often marked by boulders and agitated white water." (1):45 quote

Catchment Area "The area draining into a river, reservoir, or other body of water." *See basin or watershed.* (1):45 quote

Channel Density The ratio of the total length of stream channels in a given area to the total area. Also termed "stream density." (1):48 paraphrase; (2):715 paraphrase

Channelization Straightening and (or) deepening a pre-existing channel, or constructing a new channel, for the purpose of runoff control or navigation. (4): G-2 paraphrase

Chronic Toxicity "Toxic effect caused by long-term exposure to sub-lethal concentrations of a toxicant; sometimes refers to an effect manifested long after an exposure." *Compare to acute toxicity.* (2):713 quote

Chronostratigraphic Unit "A body of rock established to serve as the material reference for all rocks formed during the same span of time. Each of its boundaries is synchronous." (19) quote

Chinook Wind "A downslope wind in which the air is warmed by adiabatic heating." (1):50 quote

Cirque "A smallish, rounded depression with steeply sloping sides carved into the rock at the top of a ridge where a glacier has its head." (1):51 quote

Colluvium "Loose, weathered material brought to the foot of a cliff or some other slope by gravity." (6):298 quote

Conduction "The transmission of heat, electricity, or sound" through direct contact between molecules of the conducting material. (5):Section C:11 quote, paraphrase

Confluence "The meeting or junction of two or more streams." (1):61 quote

Convection The transfer of energy in a fluid medium (water or air) "by the circulation of currents from one region to another." (1):64 quote

Corrasion "The wearing away of earth materials through the cutting, scarping, scratching, and scouring effects of solid material carried by water or air." (1):65 quote

Craton "A part of the Earth's crust that has attained stability, and has been little deformed for a prolonged period. The term is now restricted to the extensive central areas of continents." (19) quote

Creep "Slow mass movement of soil and soil material down relatively steep slopes, primarily under the influence of gravity but facilitated by saturation with water and by alternate freezing and thawing." (1):67 quote

Crown Closure "The stand condition resulting in the crowns of trees touching and effectively blocking sunlight from reaching the forest floor. Crown closure is expressed as a percentage." (3):18 quote

Debris An accumulation of unsorted fragments of soil, rock, and sometimes large organic material (e.g., tree limbs). Also used to describe organic material transported within streams. (7):D.2 paraphrase

Debris Flood "Transport of large volumes of sediment and woody debris down gully systems by large volumes of water." "Debris floods do not behave as coherent flows" as the main constituent is water. "Debris floods have sediment concentrations of 20–47% by volume and characteristically have significant sediment deposits beyond the channel." (13):179, 109 quotes; (44):62 quote

Debris Flow "Rapid downstream movement of liquefied sediment and woody debris" as a coherent mass with "a plastic or semi-fluid motion similar to a viscous fluid." Includes channelized "debris flows, debris torrents and mudflows." *See slide.* (13):179 quote; (7):D.5, D.3 quotes

Debris Flow Fan "A relatively steep sloping landform shaped like an open fan or a segment of a cone, deposited by a debris flow where it exits from a narrow mountain valley onto a plain or broad valley, or wherever the channel gradient suddenly decreases. Sometimes referred to as colluvial fan." (7):D.3 quote

Debris Slide "A shallow landslide within rock debris, characterized by a displacement along one or several surfaces within a relatively narrow zone. It may take place as a largely unbroken mass, or may be disrupted into several units, each consisting of rock debris." (39) quote

Debris Torrent *A term no longer used in British Columbia. See debris flow.*

Degradation Removal of materials from one place to another via erosion, causing lowering of the elevation of streambeds and floodplains over time. The opposite of aggradation. Also used to describe the decrease of biological productivity or diversity. *See aggradation.* (11) pers. comm.

Dendochronology "The technique of dating events, determining climatic conditions, growth patterns, etc. through the use of tree rings." (1):77 quote

Depth Hoar "Large-grained, faceted, cup-shaped crystals near the ground in a snowpack. Depth hoar forms because of large temperature gradients within the snowpack." (40) quote

Dew "The droplets of water condensed from air, usually at night, onto cool surfaces." (1):83 quote

Dewater Removal of water from a streambed or waste product. (1):83 paraphrase

Dewatering "Condition in stream channel when all the water flow occurs within the permeable streambed sediments, so no surface water is left; common in small streams with considerable accumulations of" bedload. Commonly occurs in severely aggraded channels. (3):Section D quote

Diffusion "The process whereby particles of liquids, gases, or solids intermingle as the result of their spontaneous movement caused by thermal agitation and in dissolved substances move from a region of higher to one of lower concentration." (14):318 quote

Dimictic Lake A temperature "stratified lake or reservoir that experiences two periods of full mixing or (fall and spring) overturns annually" replenishing the oxygen-poor bottom water. *Compare to monomictic lake.* (1):84 quote

Discharge "Volume of water" (or other liquid, e.g., effluent) "flowing past a reference point per unit time (usually expressed as m^3/s)." (2):715 quote

Distal "Applied to a depositional environment sited at the furthest position from the source area, and generally characterized by fine-grained sediments." (39) quote

Distributary "A diverging stream that does not return to the main stream, but discharges into another stream or ocean." (1):87 quote

Ditch Block "A blockage that is located directly downgrade of a cross-drain culvert or cross-ditch and designed to deflect water flow from a ditch into a cross-drain culvert." (3):Section D quote

Drainage Basin "Total land area draining to any point in a stream, as measured on a map, aerial photo, or other horizontal, two-dimensional projection." Also termed catchment area or watershed. *See basin and watershed.* (2):715 quote

Drift "To be carried along by currents of air or water." Often specifically refers to stream invertebrates and organic material transported in water currents. Also used to describe sediments transported by glaciers and deposited directly from the ice or by glacial meltwater. (1):92 quote; (2):715 paraphrase; (15):76 paraphrase

Drought "Periods of less than average or normal precipitation over a certain period of time sufficiently prolonged to cause a serious hydrological imbalance resulting in biological losses (impact flora and fauna ecosystems) and/or economic losses (affecting man)." (1):94 quote

Drunken Trees "A group of trees leaning in all directions. Drunken trees can occur on flat permafrost-rich terrain as well as on steep terrain influenced by landslides. Also referred to as jackstrawed trees." (7):D.3 quote

Dry Valley "Linear depression that lacks a permanent stream but that shows signs of past water erosion." (39) quote

Dystrophic "Characterized by having brownish acidic waters, a high concentration of humic matter, and a small plant population. Typically used to describe a lake or pond." (1):97 quote

Ecotone "A habitat created by the juxtaposition of distinctly different habitats; an edge habitat; or an ecological zone or boundary where two or more ecosystems meet." (1):99 quote

Effluent (Stream) A stream that flows out of another stream or water body, or a stream or reach fed by groundwater; also "complex fluid waste material such as sewage or industrial refuse that is released into the environment" (especially into surface waters). *See gaining stream.* (1):101 paraphrase: (2):716 quote

Emissivity "The ratio of exitance of a body to the exitance of a black body at the same temperature." (39) quote

Ephemeral Stream A stream, whose channel is always above the water table, which flows briefly in direct response to precipitation, receiving no continued supply of water from snowmelt or springs. *Compare to intermittent stream.* (2):716 paraphrase; (8):312 paraphrase

Epilimnion The upper layer of warm water (above the thermocline) circulated by wind in a thermally stratified lake. (1):108 paraphrase

Erosion The loosening, dissolution, or wearing away, and subsequent transportation of rock and soil material by natural agents, such as water, wind and ice. (6):300 paraphrase; (7):D.4 paraphrase

Escarpment "A cliff or steep rock face of great length" formed by fault displacement, erosion, or mass movement. (8):322 quote

Esker "A narrow ridge of gravelly or sandy glacial outwash material deposited by a stream in an ice tunnel within a glacier." (1):110 quote

Estuary "Semi-enclosed body of water that has a free connection with the open ocean and within which seawater is measurably diluted with fresh water derived from land drainage." (2):716, 717 quote

Eutrophic "Rich in dissolved nutrients, photosynthetically productive, and often deficient in oxygen during warm periods." Although this condition occurs naturally, it can also be induced or accelerated by human activities (e.g., use of fertilizers and inputs of sewage effluent); the process by which this condition develops is *eutrophication*. *Compare to dystrophic, oligotrophic*. (2):717 quote

Evaporation "The physical process by which a liquid (or a solid) is transformed to the gaseous state." In hydrology, evaporation usually refers to the change in state of water from liquid to gas. *Compare to sublimation*. (1):111 quote

Evapotranspiration Loss of water to the atmosphere by the combined processes of surface evaporation (e.g., from soil or vegetation) and transpiration from metabolic use of water by plants. *See evaporation, transpiration*. (2):717 paraphrase

Fall (Earth, Rock, etc.) Extremely rapid downward movement of soil or rock material by free fall or rolling off very steep slopes. (7):D.4 paraphrase

Falling Limb The portion of the hydrograph trace immediately following the peak and reflecting the decreasing production of streamflow. *Compare to rising limb*. (1):115 paraphrase

Fault "Approximately plane surface of fracture in a rock body, caused by brittle failure, and along which observable relative displacement has occurred between adjacent blocks." (39) quote

Fen A wetland class that is covered with peat, with the water table at or near the surface, and higher nutrient content than bogs. Vegetation is characterized by sedges and grasses, and trees and shrubs may or may not be present. Fens receive both surface and subsurface water and tend to reflect the chemistry of the underlying geology, often resulting in more alkaline conditions than bogs. *Compare to bog, swamp, marsh, shallow waters*. (32) paraphrase

Fetch "The distance the wind blows over water or another homogeneous surface without appreciable change in direction." (1):119 quote

Field Capacity The amount of water held in a volume of soil after the excess water has drained away by gravity. (1):119 paraphrase

Firn "Old snow on the top of glaciers that has become granular and compact through temperature changes, forming the transition stage to glacial ice." (1):120 quote

First-Order Stream Headwater streams with no tributaries originating from seepage zones or springs; the most headward channels in the drainage network. *See stream order*. (3):Section F paraphrase; (4):G-8 paraphrase

Flocculation Aggregation of suspended inorganic and organic particles through the complex interaction of physical (e.g., shear force), chemical (e.g., electrostatic forces), and biological (e.g., extracellular polymeric substances) processes into composite particles or flocs. (16):1551 paraphrase

Flood Temporary covering of normally dry land or floodplain with rapidly accumulating surface water from flow that exceeds the bankfull capacity of a stream, channel, or reservoir (e.g., lake or ocean). *See annual flood*. (1):122 paraphrase

Flood Frequency Analysis A statistical technique that uses historical discharge records for a hydrometric station to express or measure the average time periods between floods equalling or exceeding a given magnitude. (1):123 paraphrase

Floodplain "A level, low-lying area adjacent to streams that is periodically flooded by stream water. It includes lands at the same elevation as areas with evidence of moving water, such as active or inactive flood channels, recent fluvial soils, sediment on the ground surface or in tree bark, rafted debris, and tree scarring." (3):Section F quote

Flow Duration Curve "A cumulative frequency curve that shows the percentage of time that specified discharges are equalled or exceeded." (1):128, 129 quote

Flow Path "The subsurface course a water molecule or solute would follow in a given groundwater velocity field." (1):128 quote

Flume "An open artificial channel or chute carrying a stream of water, as for furnishing power, conveying logs or as a measuring device." (1):129 quote

Fluvial "Pertaining to rivers or streams. Fluvial sediments are those deposited by streams." Also "migrating between main rivers and tributaries." *See alluvial and adfluvial*. (2):709 quote; (6):301 quote

Fog "Condensed water vapour in cloud-like masses lying close to the ground." (1):130 quote

Fog Drip "Water that is collected on the surface of vegetation and falls to the ground, as warm, moist air is advected over the vegetation." (17):424 quote

Freshet "High stream flow, usually confined to the stream channel and caused by a regularly recurring hydrological phenomenon (e.g., the snowmelt freshet) (regional term)." (3):Section F quote

Frost Heave "Ruptured soil, rock, or pavement caused by the expansion of freezing water immediately beneath the surface." *Compare to ground heave.* (1):133 quote

Froude Number "A dimensionless parameter measuring the ratio of the inertia force on an element of fluid to the weight of the fluid element—the inertial force divided by gravitational force." (18):Fluid mechanics section quote

Fry "The life stage of fish between full absorption of the yolk sac and less than 1-year old." (3):43 quote

Gaining Stream A stream or reach that receives water from the water table (i.e., groundwater seepage). *See effluent stream.* (1):135 paraphrase

Glaciofluvial "The processes, sediments, and landforms associated with glacial meltwater streams." (6):301 quote

Glaciolacustrine "Pertaining to, or characterized by, glacial and lacustrine processes or conditions applied especially to deposits made in lakes." (1):141 quote

Glide "A slow-moving, relatively shallow type of run. Calm water flowing smoothly and gently with" moderate velocities "and little or no surface turbulence." (4):G-3 quote

Graded Stream A stream characterized by a smooth, concave profile, flattening downstream, that appears to exist at a steady-state equilibrium between the rate of sediment transport and the rate of sediment supply (i.e., no net erosion or deposition of material) throughout long reaches. Lithological variations in the streambed that cause features such as waterfalls or cascades may retard or prevent stream gradation for many thousands of years. (8):486–488 paraphrase

Graupel "A snow or ice crystal heavily coated in rime." (1):141 quote

Greenhouse Gas "Carbon dioxide, water vapour, methane or any atmospheric gas that contributes the phenomenon whereby the earth's atmosphere traps solar radiation." (1):143 quote

Grike "A joint fracture in limestone, widened by solution." (19) quote

Ground Heave "Lifting of earth due to frost, overloading, swelling clay, etc." (39) quote

Groundwater Subsurface water in the zone of saturation below the level of the water table, where the hydrostatic pressure is equal to or greater than the atmospheric pressure. (3):Section G paraphrase

Gully "A channel or miniature valley cut by concentrated runoff but through which water commonly flows only during and immediately after heavy rains or during the melting of snow." (1):146 quote

Hail "Solid ice precipitation that has resulted from repeated cycling through the freezing level within a cumulonimbus cloud." (1):147 quote

Headland "A point of land, usually high with a sheer drop extending out into a body of water." (1):149 quote

Headwater "The source and upper reaches of a stream; also the upper reaches of a reservoir." Also, headwater streams are defined as having no perennially flowing tributaries. (1):149 quote; (43) paraphrase

Heat Capacity "Ratio of heat absorbed (or released) by a system to the corresponding temperature rise (or fall)." *See specific heat capacity.* (31):74 quote

Heteroscedasticity "In statistics, the degree to which the variances of two or more variables differ. Many distribution-dependent statistical tests, such as analysis of variance and the t-test assume homoscedasticity." (41) quote

Hoar Frost "Deposits of patterned ('feathered', 'needles', 'spines', etc.) ice crystals on surfaces chilled by radiation cooling. The feature is seen particularly well on vegetation. The ice is derived from the deposition of water vapour on surfaces, as well as from frozen dew." (39) quote

Humidity "Expression of the moisture content of the atmosphere. Measures of humidity include statements of the total mass of water in one cubic metre of air (absolute humidity), the mass of vapour in a given mass of air (specific humidity), relative humidity, vapour pressure, and the mixing ratio." (39) quote

Hydraulic Conductivity "In general, the ability of a rock, sediment, or soil to permit fluids to flow through it. More precisely, the hydraulic conductivity is the volume flow rate of water through a unit cross-sectional area of a porous medium under the influence of a hydraulic gradient of unity, at a specified temperature. The magnitude of hydraulic conductivity depends on the properties of both the fluid and the medium." (39) quote

Hydraulic Head "In general, the elevation of a water body above a particular datum level. Specifically, the energy possessed by a unit weight of water at any particular point, and measured by the level of water in a manometer at the laboratory scale, or by water level in a well, borehole, or piezometer in the field." (36) quote

Hydric Sites where water is "removed so slowly that the water table is at or above the soil surface all year; gleyed mineral or organic soils" are present. *See hygric, mesic, and xeric.* (20):35 quote

Hydrograph "A graphic representation or plot of changes in the flow of water or in the elevation of water level plotted against time." (1):156 quote

Hydrological Regime *See streamflow regime.*

Hydrologic Budget "An accounting of all water inflows to, water outflows from, and changes in water storage within a hydrologic unit over a specified period of time." *Also referred to as water budget* (1):157 quote

Hydrologic Recovery Process in a forest where regeneration restores the hydrology of an area to approximate pre-logging conditions. (21):25 paraphrase

Hydrologic Response Manner in which a stream or watershed reacts to a meteorological event or sequence of events. (31):19 paraphrase

Hydrology The science that describes and analyzes water, its properties, its circulation, and its distribution over the Earth's surface in natural and disturbed environments. (1):160 paraphrase; (3):Section H paraphrase

Hydrophilic Having a strong affinity for water, including the tendency to dissolve in and mix with water. *Compare to hydrophobic.* (1):160 paraphrase

Hydrophobic Lacking an affinity for water, including the tendency not to dissolve in or mix with water. *Compare to hydrophilic.* (1):160 paraphrase

Hydrostatic Pressure The pressure generated at a given depth within a liquid at rest, a function of the weight of overlying liquid. (2):719 paraphrase; (6):302 paraphrase

Hyetograph Graph or chart of precipitation intensity versus time. (28) pers. comm.

Hygric Sites where water is "removed slowly enough to keep the soil wet for most of the growing season; permanent seepage and mottling" and possible weak gleying are present. *See hydric, mesic, and xeric.* (20):35 quote

Hygrometer An instrument used to measure atmospheric humidity. (1):162 paraphrase

Hypolimnion "Lowermost, non-circulating layer of cold water in a thermally stratified lake, usually deficient in oxygen." (2):719 quote

Hyporheic Zone Zone beneath and adjacent to streams where water and dissolved chemicals move easily between surface and subsurface. (1):162 paraphrase; (22):1 paraphrase

Illuvial "Describing soil material, usually minerals and colloidal particles, that is removed from the upper soil horizon to a lower soil horizon" and "deposited from suspension or precipitated from solution." (1):164 quote; (6):302 quote

Incised Channel A channel cut into the bed of a valley floor through accelerated erosion (degradation) by flowing water of a stream or river. (1):165 paraphrase

Infiltration "The flow of fluid into a substance through pores or small openings. The word is commonly used to denote the flow of water into the soil." (1):167 quote

Infiltration Capacity The maximum rate at which water can enter a soil in a given condition. (1):167 paraphrase

Influent "Water, wastewater, or other liquid flowing into a reservoir, basin or treatment plant." Also, a stream or reach that loses water by seepage into the ground. *See losing stream.* (1):168 quote; (1):192 paraphrase

Interception "Retention of precipitation on vegetation, from which it is subsequently evaporated without reaching the ground." Interception is calculated as precipitation minus stemflow and throughfall. (2):720 quote

Intermittent Stream A stream that flows for an extended portion of the year and may support populations of some benthic invertebrates with adaptations to those environments. *Compare to ephemeral stream.* (1):171 paraphrase

Interstitial "Referring to the interstices or pore spaces in rock, soil, or other material subject to filling by water." (1):172 quote

Isohyet "A line drawn on a map connecting points that receive equal amounts of precipitation." (1):176 quote

Isostatic Rebound The upward movement of the earth's crust that follows large-scale depression of the earth because of an increase in weight. Often associated with continental glaciation where the crust was depressed by the weight of the ice. (45) paraphrase

Joint "A divisional plane or surface that divides a rock and along which there has been no visible movement parallel to the plane or surface." (19) quote

Kame "A conical hill or short irregular ridge of gravel or sand deposited in contact with glacial ice." (1):178 quote

Karst Topography Type of landforms created by the dissolution of soluble rocks, such as limestone, gypsum, and dolomite, resulting in underground drainage, depressions, sinkholes, and caves. (1):178 paraphrase

Kettle "A depression left in a mass of glacial drift, formed by the melting of an isolated block of glacial ice." (1):178 quote

Kinetic Energy The energy an object has as a result of its motion. (1):178 paraphrase

Lacustrine The processes, sediments, and landforms associated with lakes. (11) pers. comm.

Laminar Flow "A flow in which fluid moves smoothly in streamlines of parallel layers or sheets"; non-turbulent flow. (1):182 quote

Landslide Sudden mass movement of soil, debris, and rock down a slope under the influence of gravity. (7):D.6 paraphrase

Lapse Rate "The rate of change of temperature with height in the free atmosphere." (1):184 quote

Large Woody Debris Coarse woody material (conventionally greater than 10 cm in diameter and 1 m long), such as twigs, branches, logs, trees, and roots, that falls into a stream. (4):G-4 paraphrase

Latent Heat of Condensation The amount of heat energy released to the environment by a unit mass of substance when a gas changes its state to a liquid, without a change in temperature. (1):185 paraphrase

Latent Heat of Vapourization "The amount of heat absorbed by a unit mass of substance while [changing] from a liquid to a vapour state," without a change in temperature. (1):185 quote

Leaf Area Index "The total surface area of the leaves of plants in a given area divided by the area of ground covered by the plants." (35) quote

Lentic Relating to or living in standing waters such as lakes or ponds. (1):187 paraphrase

Lethal Concentration 50 (LC_{50}) "Concentration of toxicant lethal to 50% of test organisms during a defined time period and under defined conditions." (2):720 quote

Lethal Dose 50 (LD_{50}) "Dose of a chemical lethal to 50% of test organisms (rarely used with aquatic organisms because LD_{50} indicates the quantity of material injected or ingested)." (2):720 quote

Levee A natural or human-made earthen bank along the edge of a stream, lake, river, or ocean that restricts flooding. (1):187 paraphrase

Lichenometry "A technique for dating rock surfaces from measurements of the diameter of lichens growing on them." (39) quote

Limnology The scientific study of biological, physical, and geological properties of freshwater bodies. (1):189 paraphrase

Liquefaction Process by which water-saturated sediment loses strength and becomes a liquid. (1):190 paraphrase

Littoral "The region along the shore of a non-flowing body of water; corresponds to riparian for a flowing body of water. More specifically, the zone of the sea flood lying between the tide levels." (1):190 quote

Losing Stream A stream or reach that loses water by seepage into the ground. Also termed an "influent" stream. *See influent.* (1):193 paraphrase

Lotic Relating to or living in moving water such as streams or rivers. (2):721 paraphrase

Low Flow "Minimum flow or absence of flow in a stream during the dry season." *Compare to drought.* (23):5 quote

Lysimeter "A device for evaluating the water budget by enclosing a block of soil, often on a scale, with equipment for monitoring inputs and outputs." *See snowmelt lysimeter.* (17):424 quote

Macroinvertebrate "An animal without a backbone that is large enough to see without magnification" … "(e.g., most aquatic insects, snails, and amphipods)." (1):193 quote; (2):721 quote

Macrophyte Plants large enough to see without magnification, usually in reference to aquatic plants. (2):721 paraphrase

Macropore "Pore too large to hold water by capillary action." (2):721 quote

Main Stem The principal channel of a drainage system, excluding any tributaries. (2):721 paraphrase

Manning's *n* "Empirical coefficient for computing stream bottom roughness," or the "irregularity of streambed materials as they contribute to resistance to flow," which is often "used to determine water velocity in stream discharge calculations." (2):721 quote; (4):G-6 quote

Marsh A wetland landform that can be periodically or permanently flooded, is absent of trees, and usually has high nutrient content. *Compare to bog, fen, swamp, shallow waters.* (32) paraphrase

Mass Wasting "The slow or rapid gravitational movement of large masses of earth material" including creep, debris flows, and landslides, also termed mass movement. (6):303 quote, paraphrase

Matric Potential "The work per unit quantity of pure water that has to be done to overcome the attractive forces of water molecules and the attraction of water to solid surfaces. The matric potential is negative above a water table and zero below a free water table." (1):195 quote

Mean Annual Precipitation The average annual precipitation (rain and water equivalent of snow) derived from all known precipitation values, or an estimated equivalent value derived using methods such as regional indices or isohyetal maps. (1):196 paraphrase

Meander "A sinuous channel form in flatter river grades formed by the erosion on one side of the channel (pools) and deposition on the other side (point bars)." *See sinuosity.* (1):197 quote

Meandering Stream "A clearly defined channel characterized by a regular and repeated pattern of bends" formed by continued erosion on one side of the channel and deposition on the other. (15):46 quote

Mechanical Site Preparation "Any activity that involves the use of mechanical machinery to prepare a site for reforestation." (3):63 quote

Mesic Sites where water is "removed somewhat slowly in relation to supply; soil may remain moist for a significant, but sometimes short period of the year. Available soil moisture reflects climatic inputs." *See hydric, hygric, and xeric.* (20):35 quote

Monomictic Lake "Lakes or reservoirs which are relatively deep, do not freeze over during the winter, and undergo a single stratification and mixing cycle during the year (usually in the fall)." *Compare to dimictic lake.* (1):206 quote

Moraine A heterogeneous mixture of rock and soil transported and deposited by a glacier. Moraines appear as hills or ridges marking original glacial limits. (8):710, 711 paraphrase

Neoglacial "A time of increased glacial activity during the Holocene." (38) quote

Nephelometric Turbidity Unit "Measure of the concentration or size of suspended particles (cloudiness) based on the scattering of light transmitted or reflected by the medium." *See turbidity.* (2):722 quote

Nitrification "A chemical process in which nitrogen (mostly in the form of ammonia) in plant and animal wastes and dead remains is oxidized first to nitrites and then to nitrates." (12) quote

Nival Pertaining to snow. (11) pers. comm.

Nivation "Complex of surface erosional processes acting under a snow cover. It includes gelifraction, and the removal of shattered debris by solifluction and the movement of melted snow. It is an initial process in cirque development." (39) quote

Nudation "The creation of an area of bare land, either by natural events or by humans, which is the first stage in vegetation succession." (37) quote

Obligate "Without option; of a species, restricted to specific environmental conditions and thus unable to change its mode of feeding or ecological relationships." (37) quote

Off Channel "Bodies of water adjacent to the main channel that have surface water connections to the main river channel at summer discharge levels." (24):26 quote

Oligotrophic Pertaining to a lake or other body of water that is relatively low in nutrients and photosynthetic productivity, and rich in dissolved oxygen at all depths. *See dystrophic and eutrophic.* (2):723 paraphrase

Orographic Precipitation "Precipitation which results from the lifting of moist air over a topographic barrier such as a mountain range. The precipitation may occur some distance upwind and a short distance downwind, as well as on the barrier feature." (1):227 quote

Outflow Channel "A natural stream channel that transports reservoir releases." (1):228 quote

Overland Flow "The flow of rainwater or snowmelt over the land surface toward stream channels." (1):229 quote

Paraglacial Processes "The non-glacial Earth-surface processes, sediment accumulations, landforms, landsystems, and landscapes that are directly conditioned by glaciation and deglaciation. This distinguishes it from the term 'periglacial' which is defined as 'cold, non-glacial' and is applied to environments in which frost-related processes and/or permafrost are either dominant or characteristic." *Compare to periglacial.* (38) quote

Peak Flow "Greatest stream discharge recorded over a specified period of time, usually a year but often a season" or even a single event (as in storm peak flows). (2):724 quote

Percolation The movement of water through the pores or spaces of a rock or soil. (1):236 paraphrase

Perennial Stream Stream that flows all year round, regardless of weather conditions. (8):952 paraphrase

Periglacial "Applied strictly to an area adjacent to a contemporary or Pleistocene glacier or ice sheet, but more generally to any environment where the action of freezing and thawing is currently, or was during the Pleistocene, the dominant surface processes." *Compare to paraglacial processes.* (39) quote

Periphyton Assemblage of micro-organisms (e.g., algae, fungi, bacteria, protozoa) firmly attached to submerged surfaces in a stream or other water body. (1):237 paraphrase

Permafrost The thermal condition, irrespective of the state of moisture present, of any soil or rock layer where temperatures persist "below 0°C for at least two consecutive winters" without thawing in the summer. (8):833 paraphrase

Permeability A measure of the ability of soil, sediments, and rock to transmit fluids, that depends on substrate composition, compaction, and porosity. (2):724 paraphrase

Phototaxis "A change in direction of locomotion in a motile organism or cell which is made in response to a change in light intensity. The response is related to the direction of the light source." (36) quote

Phreatic "Of or relating to groundwater." (1):240 quote

Phreatic Zone "The soil or rock zone below the level of the water-table, where all voids are saturated." *See vadose zone.* (39) quote

Phreatophyte "A water-loving plant, one that thrives in wet sites and/or has the ability to" send roots to the saturated zone to use groundwater. (1):240 quote, paraphrase

Piping "The process by which water forces an opening around or through a supposedly sealed structure, such as a check dam or levee. As water flows through, the opening usually grows larger and the water carries away sediment or levee material." (1):241 quote

Plateau "An extensive, relatively flat upland." (38) quote

Pluvial Pertaining to rain; "Formed or caused by the action of rain, as a pluvial deposit" or pluvial lake. Associated with the Quaternary geological period. (1):243 quote; (8):873 paraphrase

Pool A portion of an active stream channel with reduced current velocity, typically characterized by deeper water than surrounding areas, or "a small body of standing water." (4):G-5 paraphrase, quote

Pool–Riffle Ratio "The ratio of the surface area or length of pools to the surface area or length of riffles in a given stream reach." (4):G-6 quote

Pore Water Pressure "Pressure exerted by water in the void space of soil or rock." (1):246 quote

Porosity "The property of containing openings or interstices. In rock or soil, it is the ratio (usually expressed as a percentage) of the volume of openings in the material to the bulk volume of the material. With respect to water, porosity is a measure of the water-bearing capacity of a formation. However, with respect to water extraction and movement, it is not just the total magnitude of porosity that is important, but the size of the voids and the extent to which they are interconnected, as the pores in a formation may be open, or interconnected, or closed and isolated." (1):246 quote

Postglacial "Relating to or occurring during the time following a glacial period." (1):247 quote

Precipitation Water that falls to the Earth's surface "from the atmosphere as rain, snow, hail, or sleet" following condensation caused by the cooling of air below the dew point, "measured as liquid-water equivalent regardless of the form in which it falls." (7):D.8 quote; (1):248 paraphrase

Proglacial "Applied to the area between a glacier and adjacent high ground." (39) quote

Pyranometer "An instrument which is used to measure diffuse and direct solar radiation." (37) quote

Pyrgeometer "An instrument for measuring the amount of nocturnal radiation, i.e., the amount of heat being radiated away from the Earth's surface into space." (37) quote

Rainfall Intensity–Duration Curve A curve showing the relationship between rainfall depth (or rate) and storm duration in a given area. (1):260 paraphrase

Rain-on-Snow Event Rainstorms that result in large streamflows due to the combined effects of heavy rainfall and snowmelt runoff. "Rapid snowmelt is caused by heat supplied from the warm air that is characteristic of intense rainstorms and by heat released during condensation of moisture from the air onto the snow surface." (3):Section R paraphrase, quote

Rain Shadow "A dry region on the lee side of a topographic barrier, usually a mountain range, where the rainfall is noticeably less than on the windward side." (1):261 quote

Rate-of-cut "The proportion of the watershed area allowed to be cut each year." (3):82 quote

Rating Curve A curve on a graph showing the relation between the discharge of a stream and stage at a given gauge station. (1):262 paraphrase

Rational Method A mathematical formula used to estimate "peak runoff rates from data on rainfall intensity and drainage basin characteristics." $Q = 0.278 \times CIA$, where Q is the peak runoff rate (m^3/s), C is the rational runoff coefficient, I is the rainfall intensity (mm/hr), and A is the drainage area (km^2). (26):298–299 quote, paraphrase

Reach A relatively homogeneous segment of a stream channel, lake, or inlet "characterized by uniform channel pattern, gradient, substrate, and channel confinement." (4):G-8 paraphrase, quote

Redd "Nest made in gravel, consisting of a depression hydraulically dug by a fish for egg deposition (and then filled) and associated gravel mounds." (2):725 quote

Repeatability "The quality of a test whereby repetition of the same protocol and procedures yields the same or closely similar results or responses each time. This is an important criterion of tests used in clinical diagnosis. The distinction between repeatability and reliability is that the latter is a property of the measuring instrument, whereas repeatability is determined by interaction of the observer, the subject, and the instrument." (42) quote

Resolution "(1) In remote sensing: ability of an entire remote sensor system, including lens, antennae, display, exposure, processing and other factors, to render a sharply defined image. It may be expressed in line pairs per millimetre or metre, or in many other manners. (2) Of instruments: smallest change in a physical variable which causes a variation in the response of a measuring system." (31):126 quote

Restoration The return of an ecosystem or habitat back to its original community structure, species diversity, and natural functions. (3):Section R paraphrase

Retrogression "A characteristic of a landslide, in which the upper portion of the landslide continues to fail resulting in the top of the landslide moving up slope." (7):D.9 quote

Return Flow A source of saturation-excess overland flow which occurs if the rate of interflow entering a saturated area from upslope exceeds the capacity for interflow to leave the area by flowing downhill through the soil. The excess interflow thus returns to the surface as runoff. (46) paraphrase

Return Period The time to the recurrence of a hydrological event, from statistical analysis of hydrologic data, based on the assumption that observations are equally spaced in time. A return period of 100 years means that, on average, an event of this magnitude or greater is not expected to occur more often than once in 100 years. It is calculated as the inverse of the probability of occurrence ($R = 1/p$). (1):273 paraphrase; (7):D.9 paraphrase

Revetment A facing of material used to armour a bank to protect it from erosion. *See riprap.* (4):G-6 paraphrase

Reynold's Number A dimensionless number representing the ratio of inertial and viscous forces, used to characterize the level of turbulence in fluid flow in a pipe or duct, or around an obstacle. (1):274 paraphrase

Rheotaxis "Movement of an organism in response to a current of water or air." (1):274 quote

Riffle A shallow section of a stream or river characterized by rapid current and a surface broken by completely or partially submerged obstructions such as gravel or boulders. (2):726 paraphrase; (4):G-6 paraphrase

Rill Erosion "Removal of soil particles by surface runoff moving through relatively small channels." (1):275 quote

Rime "A coating of ice, as on grass and trees, formed when extremely cold water droplets freeze almost instantly on a cold surface." (1):275 quote

Riparian (Area) "An area of land adjacent to a stream, river, lake or wetland that contains vegetation that, due to the presence of water, is distinctly different from the vegetation of adjacent upland areas." The riparian area is influenced by and influences the adjacent body of water. (3):Section R quote; (4):G-6 paraphrase

Riprap A layer of large, durable material such as coarse rock used to protect exposed surfaces and slopes susceptible to erosion such as fills and streambanks. *See revetment.* (2):726 paraphrase

Rising Limb The increasing portion of a hydrograph. *Compare to falling limb.* (1):276 paraphrase

Rock Fall The relatively free falling or precipitous movement of a newly detached segment of bedrock of any size from a cliff or other steep slope; it is the fastest form of mass movement and is most frequent in mountain areas and during spring when there is repeated freezing and thawing of water in cracks in the rock. (19) paraphrase

Rotational Failure A mass movement that occurs "on a well defined, curved shear surface," … "producing a backward rotation in the displaced mass." (7):D.9 quote

Run An area of a stream or river characterized by fast-moving water without surface agitation, where the water surface is approximately parallel to the overall gradient of the stream reach. Also, a group of fish migrating in a river that may include one of many stocks. (2):726 paraphrase; (4):G-6 paraphrase

Runoff "The portion of the precipitation that moves from the land to surface water bodies" either as surface or subsurface flow. (1):279 quote, paraphrase

Sag Pond "A small body of water occupying an enclosed depression or sag formed where active or recent fault movement has impounded drainage." (1):281 quote

Salmonid "Refers to a member of the fish family … *Salmonidae*, including the salmons, trouts, chars, whitefishes and grayling." (4):G-6 quote

Saltation "Particle movement in water or wind where particles skip or bounce along the streambed or soil surface." (1):282 quote

Saturated Flow "The liquid flow of water in soils that occurs when the soil pores in the wettest part of the soil are completely filled with water and the direction of flow is from the wettest zone of higher potential to one of lower potential." (1):284 quote

Saturation Zone The part of the soil or rock in which all pore spaces are filled with water, includes the capillary zone. *See unsaturated zone.* (1):284 paraphrase

Scarp *See escarpment.*

Scouring "The erosion action of running water in streams, which excavates and carries away material from the bed and banks. Scour may occur in both earth and solid rock material." (1):286 quote

Sea Surface Temperature "The temperature of the surface layer of sea or oceanic water." (29) quote

Secchi Disk "Black and white disk lowered into the water to measure water transparency; an average is taken of the depth at which the disk disappears when lowered and reappears when raised." "Its primary use is in the study of lakes." (1):288 quote; (2):727 quote

Sedimentation "Deposition of material suspended in water or air, usually when the velocity of the transporting medium drops below the level at which the material can be supported." (2):727 quote

Sediment Budget An accounting of the erosion, storage, and transport processes of soil and sediment in drainage basins or smaller landscape units. (11) pers. comm.

Sediment Yield "The amount of sediment transported by a stream system that may be measurable at a particular location. Usually expressed in volume or weight per unit of time." (1):291 quote

Seepage "The passage of water or other fluid through a porous medium, such as an earth embankment or masonry wall." (1):291 quote

Sensible Heat "Heat that causes a change in temperature by changing the speed at which molecules move." (37) quote

Seral Species "Plant species of early, middle, and late successional plant communities. The term is often used in a narrower sense in forest management to describe the dominant conifer vegetation that follows major disturbance episodes." (3):93 quote

Settlement Pond A basin with low water velocity that enables "suspended sediment to settle before the flow is discharged into a creek." (3):Section S quote

Shallow Waters A wetland class that encompasses basins, pools, and ponds, as well as wetlands found beside rivers, coastlines, and shorelines. Consists of submerged vegetation and floating leaved plants. *Compare to bog, fen, swamp, marsh.* (32) paraphrase

Shear Stress Stress caused by forces operating parallel to one another but in opposite directions. (11) pers. comm.

Sheet Erosion "The removal of thin layers of surface material more or less evenly from an extensive area of gently sloping land, by broad continuous sheets of running water rather than by streams flowing in well-defined channels." (7):D.10 quote

Sinkhole "A depression in the earth's surface caused by dissolving of underlying limestone, salt, or gypsum. Drainage is provided through underground channels which may be enlarged by the collapse of a cavern roof." Usually associated with karst landscapes. (1):298 quote

Sinuosity "The ratio of channel length between two points on a channel to the straight line distance between those same two points." (4):G-7 quote

Sinuous Characterized by a serpentine or winding form, typically referring to stream channels. *See meander.* (11) pers. comm.

Sleet "A form of precipitation consisting of frozen raindrops cooled to the ice stage while falling through air at subfreezing temperatures." (1):299 quote

Slide "A mass movement process in which slope failure occurs along one or more slip surfaces and in which the unit generally disintegrates into a jumbled mass en route to its depositional site." *See debris flow.* (3):Section S quote

Slough "A place of deep mud or mire; a wet or marshy place as a swamp or marshland creek. Also a side channel or inlet as from river; ordinarily found on or at the edge of the flood plain or a river." (1):300 quote

Slump "A mass movement process in which slope failure occurs on a usually curved slip surface and the unit moves downslope as an intact block, frequently rotating outward. Slumps appear as discrete block movements, often in place, whereas slides usually break up and travel downslope." (3):Section S quote

Smolt The stage in the life of salmon and similar fish in which the sub-adult individuals become physiologically adapted to saltwater and migrate down the river to begin adult life in the open sea. (36) paraphrase

Snow Density "The ratio of the volume of melt-water derived from a sample of snow and the initial volume of the sample," in mass of snow per unit volume. (1):301 quote

Snowfield "An area, usually at high elevation or in polar latitudes, where snow accumulates and remains on the ground throughout the entire year." (1):301 quote

Snow Line "The general altitude to which the continuous snow cover of high mountains retreats in summer," controlled by the depth of the winter snowpack and summer temperatures. Can also be used to identify the general altitude of the continuous snow cover at any one point in time. (1):301 quote; (1):302 paraphrase

Snowmelt Lysimeter An instrument used to "collect and measure the melt water that is released from the snow pack" during the snowmelt season. *See lysimeter.* (27):29 quote

Snow Pillow "A large rubber/neoprene bladder containing anti-freeze laid on the ground prior to snowfall. The pressure of the fluid in the bladder is measured and this enables the determination of the snow water equivalent at that location." (33) quote

Snow Water Equivalent The depth of water, usually expressed in millimetres, that would result from melting a given depth of snow. A function of the snow density. (11) pers. comm.

Soil Moisture Content "Percentage of water in soil, expressed on a dry-weight basis or by volume." (31):142 quote

Solifluction "The slow downslope viscous flow of water saturated soil and other unsorted surficial material." (7):D.10 quote

Specific Conductance "A measure of the ability of water to conduct electrical current.… related to the type and concentration of ions in solution and can be used for approximating the total dissolved solids (TDS) content of water … used in groundwater monitoring as an indication of the presence of ions of chemical substances that may have been released … by waste storage." (1):308–309 quote

Specific Heat Capacity "The amount of heat required to raise the temperature of one gram of a substance by one Celsius degree." *See heat capacity.* (1):309 quote

Spring Breakup "The breaking of a frozen river, etc. into blocks of ice at the spring thaw." (25) quote

Spume "Foam or froth on a liquid." (1):311 quote

Stage The height of the water surface of a river or lake above an arbitrarily established zero point. (14):1131 paraphrase

Stem Flow Precipitation temporarily intercepted by vegetative surfaces that eventually runs to the ground down the trunks or stems of plants. (2):728 paraphrase

Stevenson Screen "An instrument shelter with double-louvred sides that allow a free flow of air while protecting the instruments from direct sunlight and precipitation." (29) quote

Stomatal Conductance "The rate at which water vapour passes through the stomata of a plant per unit leaf area, typically measured in millimoles per square metre per second. It varies between plants, depending on the distribution density, size, and pore thickness of the stomata, and in the same plant over time according to the difference in vapour pressure between the inside of the plant and the external environment and the degree of opening of the stomatal pores." (35) quote

Stream A body of water, generally flowing in a natural surface channel. There is no formal classification to distinguish streams from rivers, creeks, etc. (31):151 paraphrase

Stream Density *See channel density.*

Streamflow The discharge of water from a surface stream course. (1):319 paraphrase

Streamflow Regime The characterization of yearly streamflow timing and volume in a watershed based on the dominant flow generation process (e.g., snow, rain, glacial, mixed). (37) paraphrase

Stream Order "A scale-dependent property of drainage networks that describes the position and approximate size of a stream segment in the network. First order streams are headwater streams that have no tributaries. A second order stream is formed where two first order streams join, a third order stream is formed where two second order streams join, etc. Note that the confluence of a second order stream with a first order stream remains a second order stream." *See first order stream.* (4):G-8 quote

Subaerial Erosion Erosion that exists or operates in the open air on or immediately adjacent to the land surface. The term is sometimes considered to include fluvial. (19) paraphrase

Sublimation The process of a solid transforming directly into gaseous form without going through the intermediate liquid stage. *Compare to evaporation.* (6):306 paraphrase

Substrate The basic surface on which material adheres, typically mineral and (or) organic material that forms the bed of a stream. (4):G-8 paraphrase

Surface Tension "A phenomenon caused by a strong attraction towards the interior of the liquid action on liquid molecules in or near the surface in such a way to reduce the surface area." (1):325 quote

Surficial Geology "Geology of surficial deposits, including soils; the term is sometimes applied to the study of bedrock at or near the Earth's surface." (19) quote

Surge A sudden forceful flow like that of a wave or series of waves. (14):1172 paraphrase

Suspended Sediment The part of a stream's (or other water body's) total sediment load that is carried in the water column through turbulence, currents, or colloidal suspension. (1):326 paraphrase

Swallet A place where a stream disappears underground, such as a cave entrance in karst regions. (31):154 paraphrase

Swamp A wetland class consisting of stagnant or slow-flowing pools with high nutrient content, usually covered with trees and shrubs. *Compare to bog, fen, marsh, shallow waters.* (32) paraphrase

Sympatry "The occurrence of species together in the same area. The differences between closely related species usually increase (diverge) when they occur together, in a process called character displacement, which may be morphological or ecological." (39) quote

Talus "Rock fragments of any size and shape, usually coarse and angular, derived from and lying at the base of a very steep, rocky slope." (7):D.11 quote

Terracettes "A series of very long and narrow terraces" or lines of steps in soil and grass, that are often discontinuous and "run parallel to the contour of the slope." "Usually produced by very local surficial slumping" on moderate to steep slopes in cool, humid climates. (7):D.11 quote; (8):1143–1145 paraphrase

Terrain A region of the Earth's surface considered as a physical feature, which can be described by relief, roughness, and surface material. (8):1145 paraphrase

Terrain Stability "Slope stability from a regional perspective as opposed to the study of the stability of an individual slope." (7):D.11 quote

Thalweg Line of deepest water in a stream channel as seen from above. Normally associated with the zone of greatest velocity in the stream. If there is no stream, it is the line of lowest points of a valley. (8):1149 paraphrase

Thermal Conductivity "A measure of the ability of a material to conduct heat." (19) quote

Thermokarst "Periglacial land-form assemblage characterized by enclosed depression (some with standing water) and so presenting a karst appearance. It is caused by the selective thaw of ground ice associated with thermal erosion by stream and lake water and may reflect climatic changes or human activity." (39) quote

Thiessen Polygons "Polygons formed by the perpendicular bisectors of the straight lines joining adjacent rainfall stations." (31):156 quote

Throughfall Precipitation that falls through the vegetative cover and eventually reaches the ground. Indirect throughfall is intercepted by foliage but eventually drips and falls to the ground, whereas direct throughfall through canopy gaps is not intercepted. *See interception.* (11, 12) pers. comm.

Time of Concentration "The time required for water to flow from the farthest point on the watershed to" an identified point in the stream. (1):334 quote

Toe "The break in slope at the bottom of a stream bank where the bank meets the bed"; or the line of a cut or fill slope where it intersects the ground or roadbed. (1):335 quote, paraphrase

Topple In British Columbia, a type of mass "movement that involves the forward rotation of a mass of soil or rock about a central point below the displaced mass." (7):D.11 quote

Total Dissolved Solids "A measure of the amount of material dissolved in water (mostly inorganic salts)." One use is to determine the quality of drinking water. (1):336 quote, paraphrase

Total Hardness The total dissolved salts in water, expressed as the equivalent concentration of calcium carbonate. Primarily due, but not limited, to calcium and magnesium in solution. (5):Section T paraphrase

Total Maximum Daily Load "The maximum quantity of a particular water pollutant that can be discharged into a body of water without violating a water quality standard." (1):337 quote

Total Suspended Solids The total amount of filterable solids found in waste or natural waters. (1):337 paraphrase

Transpiration "Passage of water vapour and other gases from a living body through membranes or pores; usually used to mean loss of water from leaves and other plant surfaces." (2):730 quote

Tree Throw *See windthrow.*

Tributary A stream that flows into another, usually larger, stream or body of water. (2):730 paraphrase

Trim Line "A line along the stream or channel below which evidence of erosion by water and/or by a debris flow is readily apparent by the erosion of soil and rock and/or by the removal of vegetation, including moss." (7):D.11 quote

Troglobite "An animal that lives its entire life within a cave and is specifically adapted to life in total darkness." (37) quote

Turbidity An optical measure of the reduced transparency of water due to suspended material, which causes incident light to be scattered, reflected, and attenuated. *See nephelometric turbidity unit.* (1):346 paraphrase

Unsaturated Zone The subsurface zone in the soil between the water table and the soil surface where the pores contain both air and water, not including the capillary zone. Also termed the zone of aeration. *See saturation zone.* (1):349 paraphrase

Vadose Zone "The zone between the land surface and the water table … The pore spaces contain water at less than atmospheric pressure, as well as air and other gases. Saturated bodies, such as perched groundwater, may also exist in the vadose zone." *See phreatic zone.* (30):560 quote

Variable Source Area Saturated zone, adjacent to a stream channel, which varies in size seasonally and during individual storm events, and contributes runoff to the channel during a runoff-producing event. (11) pers. comm.

Varve "A layer or series of layers of sediment deposited in a body of still water in one year." (1):353 quote

Vernal Pool "Wetlands that occur in shallow basins that are generally underlain by an impervious subsoil layer or bedrock outcrop, which produces a seasonally perched water table." (1):353 quote

Water Balance An accounting of the balance between the amount of water entering (inputs) and the amount of water leaving a system (outputs), at the watershed level. (1):358 paraphrase

Waterbar A shallow channel or raised barrier, laid diagonally across the surface of a road to guide water off the road, preventing "excessive flow down the road surface and" subsequent "erosion of road surface materials." (2):731 paraphrase; (3):Section W quote

Water Content "The amount of water that is present in the air, or in a material such as wood or soil, where it is usually expressed as a percentage of the oven dry weight of that material." (37) quote

Water Cycle The cyclic process of water travelling in a sequence from the air (condensation) to the earth (precipitation) and returning to the atmosphere (evaporation). *See hydrological cycle.* (1):359 paraphrase

Water Quality The physical, chemical, and biological properties of water related to a particular use. (1):364 paraphrase

Water Retention Curve "Graph representing the suction pressure versus the moisture or water content in an unsaturated soil." (31):127 quote

Watershed Also referred to as a drainage basin or catchment area. "Watersheds are the natural landscape units from which hierarchical drainage networks are formed." Watershed boundaries typically are the height of "land dividing two areas that are drained by different river systems." (1):367 quote; (4):G-8 quote

Watershed Assessment A process for evaluating the cumulative impacts, over time and space, of all land use activities within a given watershed on variables such as streamflows, sediment regime, riparian health, and landscape and stream channel stability. The process can also be used to assess the potential impacts of proposed future land use activities. (11) pers. comm.

Water Table "The level in the ground below which all pore spaces are saturated with water." The surface along which water pressure equals atmospheric pressure. (6):307 quote

Water Yield The volume of water produced by all or part of a drainage basin through either surface channels or subsurface flow for a defined period of time. (1):370 paraphrase; (5):Section W paraphrase

Weathering "The physical disintegration or chemical decomposition of rock due to wind, rain, heat, freezing, thawing, etc." (1):370 quote

Weir "Notch or depression in a dam or other water barrier through which the flow of water is measured or regulated. Also, a barrier constructed across a stream to divert fish into a trap or to raise the water level or divert water flow." (2):731 quote

Wetted Perimeter "The length of the wetted contact between a stream of flowing water and its containing conduit or channel, measured in a plane at right angles to the direction of flow." (1):378 quote

Windfirm "Of trees, able to withstand strong winds (i.e., to resist windthrow, windrocking, and major breakage)." (3):117 quote

Windthrow "Tree or trees felled or broken by the wind." *Also called blowdown, tree throw.* (3):117 quote

Woody Debris "Coarse wood material such as twigs, branches, logs, trees, and roots that fall into streams." (1):383 quote

Xeric Site where "water is removed very rapidly in relation to supply; soil is moist for brief periods following precipitation." *See hydric, hygric, mesic.* (20):35 quote

Zonal Flow "The winds that blow in a mainly west-to-east or east-to-west direction, and particularly to the main, broad airstreams of the general or large-scale atmospheric circulation." (39) quote

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ACRONYMS AND INITIALISMS

AAC	allowable annual cut
ABCFP	Association of British Columbia Forest Professionals
ADCP	acoustic Doppler current profiler
AMS	accelerator mass spectrometry
APEGBC	Association of Professional Engineers and Geoscientists of British Columbia
AO	Arctic oscillation
ASCE	American Society of Civil Engineers
AVHHR	advanced very high resolution radiometer
BACI	before-after control-impact
BEC	biogeoclimatic ecosystem classification
BMP	best management practice
BOD	biological oxygen demand or biochemical oxygen demand
bp	before present
CAP	channel assessment procedure
CC	clearcut or climate change
CCME	Canadian Council of Ministers of the Environment
CEC	cation exchange capacity
CFFG	coastal fisheries/forestry guidelines
CMD	climatic moisture deficit
CMZ	channel migration zone
CP	cutting permit
CPOM	coarse particulate organic matter
CRHM	cold region hydrological model
CWAP	coastal watershed assessment procedure
CWD	coarse woody debris
CWE	cumulative watershed effect
CWG	community watershed guidelines
CWH	Coastal Western Hemlock
D_{50}	size for which 50% of the sampled material is finer; also D_{84} and D_{95}
dbh	diameter at breast height
DDM	delegated decision maker
DEM	digital elevation map
DFAM	defined forest area management
DFO	Department of Fisheries and Oceans, Canada
DHSVM	Distributed Hydrology Soil Vegetation Model
DLM	digital landform model
DM	District Manager or Deputy Minister
DO	dissolved oxygen
DOC	dissolved organic carbon
DOM	dissolved organic matter
DTM	digital terrain map or modelling
DTSM	detailed terrain stability mapping
EBM	ecosystem-based management
EC	electrical conductivity
ECA	equivalent clearcut area
ELJ	engineered logjam
ENSO	El Niño southern oscillation
EPA	Environmental Protection Agency (U.S.)
ERA	equivalent roaded area
ESA	environmentally sensitive area
ESCM	earth system climate model
ET	evapotranspiration
FAO	Food and Agriculture Organization
FDP	forest development plan
FDR	frequency-domain reflectometer
FEMAT	forest ecosystem management assessment team
FFG	functional feeding group
FFIP	Fish–Forestry Interaction Program
FIA	Forest Investment Account
FIZ	forest inventory zone
FOC	Fisheries and Oceans Canada
FPA	*Fish Protection Act*
FPB	Forest Practices Board
FPC	Forest Practices Code
FPOM	fine particulate organic matter
FPPR	Forest Planning and Practices Regulation
FRBC	Forest Renewal British Columbia
FRPA	*Forest Range and Practices Act*
FSC	Forest Stewardship Council of Canada
FSP	forest stewardship plan
FSR	forest service road
FSW	fisheries sensitive watershed
FSZ	fisheries sensitive zone
FWA	Federal Watershed Analysis
GAP	gully assessment procedure
GCM	global climate model

GIS	geographic information system
GPS	global positioning system
GRACE	gravity recovery and climate experiment
HADD	harmful alteration, destruction, or disruption
HSPF	hydrological simulation program-FORTRAN
ICWEP	Idaho cumulative watershed effects procedure
IFFWG	interior fish, forestry, and wildlife guidelines
IPCC	Intergovernmental Panel on Climate Change
IPP	independent power project (or producer)
IRM	integrated resource management
IWAP	interior watershed assessment procedure
IWMP	integrated watershed management plan
KFA	karst field assessment
LAI	leaf area index
LC_{50}	lethal concentration to 50% of the organisms
LD_{50}	lethal dose to 50% of the organisms
LMU	landscape management unit
LMZ	lakeshore management zone
LOD	large organic debris
LRMP	land and resource management plan
LWD	large woody debris
LWM	large woody material
MAL	Ministry of Agriculture and Lands, British Columbia
MODIS	moderate resolution imaging spectro-radiometer
MOE	Ministry of Environment, British Columbia
MOELP	Ministry of Environment, Lands and Parks, British Columbia
MOF	Ministry of Forests, British Columbia
MFR	Ministry of Forests and Range, British Columbia
MOT	Ministry of Transportation, British Columbia
MOTH	Ministry of Transportation and Highways, British Columbia
MPB	mountain pine beetle
MSC	Meteorological Service of Canada
MSRM	Ministry of Sustainable Resource Management, British Columbia
MSZ	marine-sensitive zone
MWLAP	Ministry of Water, Land and Air Protection, British Columbia
NADXX	North American Datum XX= year (i.e., NAD83 = 1983 datum)
NCWAP	North Coast Watershed Assessment Program
NFR	non-filterable residue
NOEL	no observed effect level
NPF	not properly functioning
NTDB	national topographic database
NTS	national topographic system
NTU	nephelometric turbidity unit
OWAP	Oregon Watershed Assessment Process
PAR	photosynthetically active radiation
PC	partial cut
PDO	Pacific decadal oscillation
PFC	proper functioning condition
PFZ	pesticide-free zone
PHSP	pre-harvest silviculture prescription
PNA	Pacific North American pattern
PNW	Pacific Northwest
POC	point of commencement
POI	point of intersection
POT	point of termination
ppm	parts per million
PPT	precipitation
PSP	permanent sample plot
QCI	Queen Charlotte Islands (now Haida Gwaii)
RAR	Riparian Area Regulation
RCC	river continuum concept
RFID	radio frequency identification
RHA	riparian habitat area
RISC	Resource Information Standards Committee, British Columbia (formerly Resources Inventory Committee)
RMA	riparian management area or resource management agreement
RMZ	riparian management zone or resource management zone
RPM	riverine productivity model
RRZ	riparian reserve zone
RTD	resistance temperature detector
RTSM	reconnaissance terrain stability mapping
SAR	snow accumulation recovery
SC	specific conductance
SCQI	stream crossing quality index
SF	stemflow
SLP	sea-level pressure
SOP	standard operation procedures
SP	silviculture prescription or site plan
SRP	soluble reactive phosphorus
SST	sea surface temperature
SWE	snow water equivalent
TDN	total dissolved nitrogen
TDP	total dissolved phosphorus

TDR	time-domain reflectometer
TDS	total dissolved solids
TERP	terrestrial ecosystem restoration program
TF	throughfall
TFL	tree farm licence
TMDL	total maximum daily load
TOC	total organic carbon
TRIM	terrain resource information management
TSA	timber supply area
TSIL	terrain survey intensity level
TSM	terrain stability mapping
TSS	total suspended solids or temperature sensitive stream
USDA	United States Department of Agriculture
UV	ultraviolet
VIC	variable infiltration capacity
WAP	watershed assessment procedure
WGS 84	world geodetic system 1984
WMO	World Meteorological Organization
WP	working plan
WRENSS	water resource evaluation of non-point silvicultural sources
WRP	watershed restoration program
WSC	Water Survey of Canada
WWA	Washington Watershed Analysis

Reference

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SYMBOLS

A	area
a	annum
C	carbon
°C	degrees Celsius
Ca	calcium
cal	calories
Cd	cadmium
cfd	cubic feet per day
cfs	cubic feet per second
CI	confidence interval
Cl	chlorine
cm	centimetre
cmd	cubic metres per day
cms	cubic metres per second
Cu	copper
CV	coefficient of variation
d	depth or day
dam	decametre
E	east
e.g.	(*exempli gratia*) for example
et al.	(*et alia*) and others
Fe	iron
Fr	Froude number
ft	foot
g	gram
gal	gallon
H	hydrogen
ha	hectare
HCN	hydrogen cyanide
Hg	mercury
ibid.	(*ibidem*) in the same place
i.e.	(*id est*) that is
in	inch
J	joule
K	potassium
ka	kiloannum
kg	kilogram
km	kilometre
kPa	kilopascal
L	litre
lb	pound
m	metre
M	mass
mb	millibar
mg	milligram
Mg	magnesium
mi	mile
min	minute
MJ	megajoule
mm	millimetre
Mn	manganese
mol	mole
MPa	megapascal
n	Manning's roughness coefficient
N	Newton or north or nitrogen
Na	sodium
$Na_4Fe(CN)_6$	sodium ferrocyanide
NH_3	ammonia
NH_4^+	ammonium

NH_4NO_3	ammonium nitrate	Si	silicon
NO_2^-	nitrite	SO_4^{2-}	sulphate
NO_3^-	nitrate	θ	water content
φ	angle of repose	Δt	time interval
ρ	density	t	metric ton
oz	ounce	τ	shear stress
P	probability	λ	wavelength
P	perimeter or phosphorus	μ	micron or mean of population
Pa	Pascal	μS	Micro Siemens
pH	negative log of hydrogen ion activity	*v*	velocity
PO_4^{3-}	phosphate	V	volume or volt
Q	discharge rate	w	width
R_e	Reynolds number	W	watt or west
r^2	coefficient of determination	W_b	channel bankfull width
s	second	yd	yard
S	sulphur or Siemens or south	yr	year
SD	standard deviation	Zn	zinc
SE	standard error		

CONVERSION FACTORS

Distance

1 mm = 0.0393701 in	1 in = 25.4 mm
1 cm = 0.3937008 in	1 in = 2.54 cm
1 m = 3.2808399 ft	1 ft = 0.3048 m
1 m = 1.0936133 yd	1 yd = 0.9144 m
1 km = 0.6213712 mile	1 mi = 1.609344 km

Area

1 cm^2 = 0.1550003 in^2	1 in^2 = 6.4516 cm^2
1 m^2 = 10.7639104 ft^2	1 ft^2 = 0.092903 m^2
1 m^2 = 1.19599 yd^2	1 yd^2 = 0.8361274 m^2
1 ha = 2.4710538 acre	1 acre = 0.4046873 ha
1 km^2 = 247.1053815 acres	1 acre = 0.0040469 km^2
1 km^2 = 0.3861006 $mile^2$	1 mi^2 = 2.5899831 km^2

Volume

1 cm^3 = 0.0610237 in^3	1 in^3 = 16.3870641 cm^3
1 L = 0.2641721 U.S. gal	1 U.S. gal = 3.7854118 L
1 L = 0.2199692 imp gal	1 imp gal = 4.54609 L
1 L = 0.001 m^3	1 m^3 = 1000 L
1 U.S. gal = 0.8326742 imp gal	1 imp gal = 1.2009499 U.S. gal
1 m^3 = 219.9692483 imp gal	1 imp gal = 0.0045461 m^3
1 m^3 = 35.3146666 ft^3	1 ft^3 = 0.0283168 m^3
1 m^3 = 264.1720512 U.S. gal	1 acre-ft = 325 851.43326 U.S. gal
	1 acre-ft = 271 328.0765053 imp gal
	1 acre ft = 1 233.4818553 m^3
1 m^3= 0.0001 ha-m	
1 ha-m = 8.1071318 acre-ft	1 acre-ft = 0.1233482 ha-m
1 km^3 = 0.2399128 $mile^3$	1 $mile^3$ = 4.1681818 km^3

Mass

1 g =	0.035274 oz	1 oz =	28.3495231 g
1 kg =	2.2046226 lb	1 lb =	0.4535924 kg
1 kg =	0.001 t	1 t =	1000 kg
1 t =	1.1023113 U.S. tons	1 ton =	0.9071847 t

Pressure

1 pascal (Pa) =	1 N/m^2 (1 kg × m/s^2)		
1 kPa (1000 Pa) =	0.01 bars	1 bar =	1×10^5 Pa
1 lb/in^2 (psi) =	6.89×10^3 Pa	1 Pa =	1.45×10^{-4} psi
1 atmosphere (atm) =	1.01325×10^5 Pa	1 Pa =	9.86926×10^{-6} atm
1 mm Hg =	133.32 Pa	1 Pa =	0.00750062 mm Hg
1 mm Hg =	0.00133322 bars	1 bar =	750.062 mm Hg

Discharge equivalents

1 m^3/s =	35.3146662 ft^3/s	1 ft^3/s =	0.0283168 m^3/s
1 ft^3/day =	0.0283168 m^3/day	1 m^3/day =	35.3146662 ft^3/day
1 acre-ft/s=	1 233.48184 m^3/s	1 m^3/s =	0.0008107 acre-ft/s

Unit discharge conversion to mm

Depth of runoff (m) = discharge (m^3/s) × Δt (s)/basin area (m^2)
and
Depth of runoff (mm) = depth of runoff (m) × 1000 mm/m

For example, if annual mean flow = 1 m^3/s from a 100 km^2 catchment, then:
Depth of runoff (m) = (1 m^3/s)(365.25 d)(86 400 s/d)/[(100 km^2)(1000 m/km)^2]
= 0.315576 m
and
Depth of runoff (mm) = 0.315576 m × 1000 mm/m
= 315.576 mm

EXPRESSION OF QUANTITIES

Generally, quantities of substances can be expressed as either mass or volume, depending on the form of the substance (i.e., typically aqueous substances are reported volumetrically and solids are expressed as mass). Mass and volume are related by the density of the particular substance:

$$\rho = \frac{M}{V} \qquad (1)$$

where: M is the mass (kg), V is volume (m^3), and ρ is the density (kg/m^3). Liquid water has a relatively constant density over the normal range of temperatures and pressures encountered in hydrology, and for hydrologic purposes can be set equal to 1000 kg/m^3. Because of the relatively constant density, the volume of liquid water represents a reliable measure of quantity, which is often more convenient to use than mass. In fact, the volume of water is especially important when considering a liquid occupying a specified area:

$$V = d \times A \qquad (2)$$

where: d is the depth (m) and A is the area (m^2).

In hydrology, it is often necessary to determine the rate of exchange of water (or other substance such as pollutant) as the total or the average amount transferred in a specific time interval. The general expression is:

$$\text{Rate} = \frac{\text{quantity}}{\Delta t} \qquad (3)$$

where: Δt is the time interval (s, min, hr) and the quantity could be expressed as a mass, volume, or depth. For example, the total volume (V) of water (m^3) leaving a catchment in a time interval Δt (s) at a discharge rate of Q (m^3/s) is:

$$V = Q \times \Delta t \tag{4}$$

Working with units of measurement

Hydrologic calculations frequently require working with and converting units of measurement. The key principle is that the rules of algebra for multiplication and division apply to units in the form of dimensional analysis. For example, suppose we want to convert a depth measurement of 5 feet to its equivalent in metres. We would multiply the measurement in feet by a ratio formed from the conversion 1 m ≈ 3.281 ft, with the desired unit in the numerator and the current unit in the denominator:

$$(5\ \text{ft})\left(\frac{1\text{m}}{3.281\ \text{ft}}\right) = 1.524\ \text{m} \tag{5}$$

Note that if we have units to a power (such as area), then we need to multiply by the conversion factor by the same number of times as the exponent number to maintain the correct dimensions. For example, to convert an area of 4 ft^2 to m^2:

$$(4\ \text{ft}^2)\left(\frac{1\text{m}}{3.281\ \text{ft}}\right)\left(\frac{1\text{m}}{3.281\ \text{ft}}\right) = (4\ \text{ft}^2)\left(\frac{1\text{m}}{3.281\ \text{ft}}\right)^2 \tag{6}$$

$$= 0.3716\ \text{m}^2$$

Noting that some quantities are expressed in compound units will simplify the conversion process. For example, force is expressed in Newtons (N), where:

$$1\ \text{N} = 1\ \text{kg} \times \text{m/s}^2 \tag{7}$$

Pressure is force per unit area, with an SI unit of Pascal (Pa), such that:

$$1\ \text{Pa} = 1\ \text{N/m}^2 = \frac{1\text{kg}}{(\text{m} \times \text{s}^2)} \tag{8}$$

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Climate	Temperature, relative humidity, precipitation, wind speed, and wind direction	1970–present	British Columbia	Ministry of Forests and Range, Wildfire Management Branch	Approximately 260 hourly reporting automated weather stations operated April 15 to October 15 by the B.C. Fire Weather Network, with some year-round. Website has locations of stations and data at 14:00 and 16:00 hr during fire season.	Complete data set kept by Protection Program. One can subscribe to receive current data, or historic data set can be purchased on CD. **Fire weather:** http://bcwildfire.ca/Weather/	Ministry of Forests and Range PO Box 9502, Stn Prov Govt Victoria, BC V8W 9C1 Tel: 250-387-5965
Climate	Temperature, relative humidity, precipitation, wind speed, and wind direction	Unknown	British Columbia	Ministry of Forests and Range, Forest District offices	Manual, daily fire weather data for field operations, number of stations and time operated varies annually.	No website, data kept at Forest District offices, some transferred to Fire Protection Program.	Ministry of Forests and Range District Offices Tel: 250-387-5965
Climate, Snow	Precipitation, temperature, wind, air pressure, humidity, snowpack conditions, and frost	Some since 1974	British Columbia	Ministry of Transportation, Snow Avalanche and Weather Program	Historically manual stations, now automated (hourly) weather stations used. • 46 RAWS stations for avalanches at high elevations • 54 RWS stations for road conditions • 50 frost probe stations on roads	Data kept at headquarters. **Construction Maintenance Branch, Avalanche and Weather Programs:** www.th.gov.bc.ca/mot_org/const_maint/avalanche_weather/	Avalanche and Weather Programs Ministry of Transportation PO Box 9850, Stn Prov Govt Victoria, BC V8W 9T5 Tel: 250-387-6931
Climate, Water	Rainfall, snow accumulations, water inflow to reservoirs, sediment input from sub-drainages, and periodic water samples for water quality of city drinking water, including micro-organisms	~1960s	British Columbia	Metro Vancouver	Water monitoring and forecasting: monitoring over 20 meteorological stations in Metro Vancouver watersheds and sampling over 20 reservoirs.	Data kept at Watershed Management Department. Daily values updated online. **Water turbidity info:** www.metrovancouver.org/services/water/Pages/default.aspx **Metro Vancouver home page:** www.metrovancouver.org/Pages/default.aspx	Metro Vancouver Head Office 4330 Kingsway Burnaby, BC V5H 4G8 Tel: 604-432-6200

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Climate, Water quality	Reservoir depths, rainfall, and water quality, including physical, chemical, and biological parameters	~1960s; online since 2000	British Columbia	Capital Regional District, Integrated Water Services	Data records from above and below treatment facilities.	**Water quality data** (since 2000): www.crd.bc.ca/water/waterquality/reports.htm **Sooke Reservoir historical storage** (since 2000): www.crd.bc.ca/water/watersupplyarea/summary.htm Older data available from Integrated Water Services. **Capital Regional District Water Services:** www.crd.bc.ca/water/index.htm	Capital Regional District Water Services 479 Island Highway Victoria, BC V9B 1H7 Tel: 250-474-9600
Climate, Snow, Water	Reports and data on daily snow water equivalent, maximum and minimum temperature, and cumulative precipitation by station	Snow surveys 1935–present; snow pillow mid-1980s–present	British Columbia	Ministry of Environment, River Forecast Centre	Provides reports on snowpack. Snow Data Archives include historical snow survey data and snow pillow data for over 150 stations. Near real-time automatic snow pillow data from remote monitoring stations (subject to errors).	**Snow-and-river level data:** www.env.gov.bc.ca/rfc/data/ **River Forecast Centre:** www.env.gov.bc.ca/rfc/	River Forecast Centre Ministry of Environment PO Box 9362 Stn Prov Govt Victoria, BC V8W 9M1 Tel: 250-387-9472
Climate	Daily temperatures, monthly precipitation, surface pressure, surface wind	1874–present	Canada	Environment Canada, Science and Technology Branch, Climate Research Division	Rehabilitated precipitation and homogenized temperature data sets: • daily temperatures 1895–present for 210 locations • monthly precipitation (snow and rain) for 462 sites 1900–present • surface pressure data for 630 stations from 1953 • surface wind speeds for 117 stations from 1953 • sites in the Canadian Artic since the 1940s.	**Environment Canada, adjusted historical Canadian climate data:** www.cccma.bc.ec.gc.ca/hccd/	Climate Research Division, Science and Technology Branch Environment Canada 4905 Dufferin Street Downsview, ON M3H 6H9

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Climate	Temperature, precipitation, relative humidity, atmospheric pressure, wind speed, wind direction, visibility, cloud types, cloud heights and amounts, soil temperature, evaporation, solar radiation, sunshine, and weather phenomena	Some 1900s–present	Canada	Environment Canada, Meteorological Service of Canada	National Climate Data (CD) and Information Archive: hourly data for specific locations and dates; includes climate averages and extremes; will respond to customized requests.	**National climate data and information archive:** http://climate.weatheroffice.gc.ca/Welcome_e.html	Environment Canada Pacific and Yukon Region Meteorological Service of Canada 120–1200 West 73rd Avenue Vancouver, BC V6P 6H9 Climate Services Tel: 604-664-9067 ClimatePYR@ec.gc.ca
Climate, Snow, Water supply, GIS products	Precipitation, temperature, snow water equivalent, and depth of snow	1997–present	United States (some states)	U.S. Department of Agriculture, Natural Resources Conservation Service, National Water and Climate Center	Over 200 stations located in the western United States.	**National Water and Climate Center:** www.wcc.nrcs.usda.gov/	U.S. Department of Agriculture Natural Resources Conservation Service National Water and Climate Services 1201 NE Lloyd Blvd, Suite 802 Portland, OR 97232-1274 USA
Climate change	Downscaled reference and projected temperature and precipitation	Normals for 1961–1990, GCM projections for 2020s, 2050s, 2080s	British Columbia, Yukon, parts of Alberta and Alaska	Ministry of Forests and Range, Research Branch	Downscaled PRISM data for western Canada.	**ClimateBC:** www.genetics.forestry.ubc.ca/cfcg/climate-models.html	D.L. Spittlehouse B.C. Ministry of Forests and Range Research Branch Victoria, BC Tel: 250-387-3453 dave.spittlehouse@gov.bc.ca
Fish	Salmon escapements, fish stocking records for streams and lakes, depth maps for over 2500 lakes, and reports	1950s–present	British Columbia	Freshwater Fisheries Society of BC, Ministry of Environment, and Fisheries and Oceans Canada	Current information on fish in provincial lakes and streams. • FishWizard queries an interactive map • Fisheries Information Summary System queries the database and documents • New data are recorded at Field Data Information System for uploading of field data collected to RISC standards	**Fisheries Inventory:** www.env.gov.bc.ca/fish/fidq/index.html	Government of British Columbia Fisheries Inventory: fish.issues@gov.bc.ca

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Fish	Fisheries reports	Unknown	Canada	Libraries of Fisheries and Oceans Canada (WAVES)	Library network in Fisheries and Oceans Canada containing bibliographic information about literature relating to fisheries.	**WAVES:** http://intero1.dfo-mpo.gc.ca/waves2/index2.html	Libraries of Fisheries and Oceans Canada oofi@dfo-mpo.gc.ca Fisheries and Oceans Canada Library 200–401 Burrard Street Vancouver, BC V6C 3S4 Tel: (604) 666-3851 paclibrary@pac.dfo-mpo.gc.ca
Fish	Reports on fish habitat, fish, wetlands, riparian, and streams	1987–present	British Columbia	Ministry of Environment, Environmental Stewardship Division, Ecosystems Branch	Fish habitat information, including fish fact sheets, best management practices for works in and adjacent to streams, and wetland evaluations.	**Fish and habitats:** www.env.gov.bc.ca/wld/fishhabitats/index.html **Fish factsheets:** www.env.gov.bc.ca/wld/fishhabitats/fishfactsheets.html **Guidelines and best management practices:** www.env.gov.bc.ca/wld/BMP/bmpintro.html	Ministry of Environment Ecosystems Branch Environmental Stewardship Division PO Box 9338, Stn Prov Govt, Victoria, BC V8W 9M1 wildlife@victoria1.gov.bc.ca
Fish	Fish species presence and distribution, marine habitat, administrative boundaries, Canadian Hydrographic Service charts, and orthophoto imagery	Unknown	British Columbia, Yukon	Fisheries and Oceans Canada	Access to fish and fish habitat information (over 200 data sets) queried through an interactive map interface.	**Mapster:** www.canbcdw.pac.dfo-mpo.gc.ca/ows/imf.jsp?site=mapster	Fisheries and Oceans Canada B.C. and Yukon Regional Headquarters 200–401 Burrard Street Vancouver, BC V6C 3S4 hebgis@pac.dfo-mpo.gc.ca
Fish, Animals	Species at risk, location maps, and level of protection	1991–present	British Columbia	Ministry of Environment, Conservation Data Centre	Information on animals, plants, and plant communities at risk in province. Computerized database with status list, map of known locations, and list of levels of protection.	**Conservation Data Centre home:** www.env.gov.bc.ca/cdc/	Ministry of Environment Ecosystems Branch Conservation Data Centre PO Box 9358, Stn Prov Govt Victoria, BC V8W 9M2 Tel: 250-356-0928 cdcdata@gov.bc.ca

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Fish, Geography	Orthophotos, base maps, fisheries resources, fish distribution, and legal boundaries	Some from 1992	British Columbia, Yukon	Fisheries and Oceans Canada	Spatial data holdings: orthophotos, base maps, and data sets (from many sources) on fisheries regions.	**Spatial data holdings:** www.pac.dfo-mpo.gc.ca/gis-sig/holdings-archives-eng.htm	Fisheries and Oceans Canada B.C. and Yukon Regional Headquarters 200–401 Burrard Street Vancouver, BC V6C 3S4
Fish, Animals	Species at risk, and species occurrence and ranges	Unknown	Canada	Environment Canada, Canadian Wildlife Service, Species at Risk Branch	*Species at Risk Act* maps and lists of species at risk, produced from species occurrence and other data.	**Species at risk home:** www.sararegistry.gc.ca/default_e.cfm	Species at Risk Registry Office 351 St. Joseph Boulevard, 21st Floor Gatineau, QC K1A 0H3 SARAregistry@ec.gc.ca
Geography, Water bodies	Unique water body identification	Unknown	British Columbia	Ministry of Environment, Environmental Ecosystems Branch,	Watershed Atlas 1:50 000 digital maps of provincial stream networks with watershed boundaries of third-order and larger streams provided in downloadable files. Provides unique identification of all water bodies; 1:20 000 mapping is currently being compiled.	**1:50 000 watershed atlas maps** (and links): www.elp.gov.bc.ca/fish/watershed_atlas_maps/index.html	Ministry of Environment Ecosystems Branch PO Box 9358, Stn Prov Govt Victoria, BC V8W 9M2 Tel: 250-387-2735
Geography, Land use	Historical maps, plans, architectural drawings, and charts	1848–present	British Columbia	Royal British Columbia Museum Corporation, BC Archives	BC Archives provides online access to cartographic records.	**Cartographic records:** www.bcarchives.gov.bc.ca/cartogr/general/maps.htm	Royal British Columbia Museum 675 Belleville Street Victoria, BC V8W 9W2 Tel: 250-387-2072 access@www.bcarchives.gov.bc.ca
Geography, Mapping, Imaging	Maps, orthophotos, digital mapping references, air photo index, and geographical names	Air photos 1936–present	British Columbia	GeoBC, provincial geographic information warehouse	Provides a range of mapping services including: • Provincial baseline atlas: digital road atlas (TRIM) and orthophotos • Geospatial reference: location of control monuments • Air photo inventory (1979–2003 online) • Geographical names • Digital maps of province • GPS corrections—CDGPS.	**GeoBC home:** http://archive.ilmb.gov.bc.ca/geobc/index.html	GeoBC Crown Registry and Geographic Base PO Box 9375, Stn Prov Govt Victoria, BC V8W 9M2 Tel: 250-952-5304 crgb.info@gov.bc.ca

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Geography, Mapping	Various spatial data	Various, depending on data layer	British Columbia	Hectares BC, created by the Biodiversity BC partnership	A wiki providing a range of spatial data to users without the need for GIS skills to carry out planning, assessment, reporting, and decision-making functions.	**Hectares BC home:** www.hectaresbc.org/app/habc/HaBC.html	Biodiversity BC: info@biodiversitybc.org
Geography, Metadata	Administrative boundaries, ecosystem mapping, and wildlife habitat	Unknown	British Columbia	Ministry of Agriculture and Lands, Integrated Land Management Bureau, Land and Resource Data Warehouse	Published ARC/Info GIS data sets on an FTP site.	**Land and Resource Data Warehouse:** www.lrdw.ca Also see GeoBC	LRDW@geobc.gov.bc.ca or see GeoBC
Geography, Ecosystems	Ecosystem maps	2003	British Columbia	Ministry of Forests and Range, Research Branch	Downloadable digital and information on ordering paper copies of biogeoclimatic ecosystem classification maps.	**BECWeb maps and mapping:** www.for.gov.bc.ca/HRE/becweb/	Ministry of Forests and Range Research Branch BEC Program Bag 6000, 3333 Tatlow Road Smithers, BC V0J 2N0
Geography, Fish	Water body mapping, fish distribution maps, and coastal resource maps	1993	British Columbia	Community Mapping Network (provincial and local government and community groups)	Provides mapping of community natural resource themes, includes provincial maps and more detailed information for Georgia Basin and Central Okanagan.	**Community Mapping Network:** http://cmnbc.ca/	Ministry of Environment Lower Mainland Region 10470 152nd Street Surrey, BC V3R 0Y3
Geography	Maps, satellite photos, and administrative boundaries	Landsat 1984–1989; RADARSAT 1989–1999	Canada	Natural Resources Canada, Earth Sciences Sector, Canada Centre for Remote Sensing	Geospatial data of Canada. Databases include: • Landsat • RADARSAT • atlas of federal boundaries • Canadian Land Inventory. Distributes small-scale geospatial data for Canada at no charge.	**GeoGratis:** http://geogratis.cgdi.gc.ca/	Natural Resources Canada GeoGratis Client Services 2144, King West Street, Suite 010 Sherbrooke, QC J1J 2E8 geoginfo@nrcan.gc.ca

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Geography	Maps, spatial mapping references, and climate change information	~1905–present	Canada	Natural Resources Canada, Earth Sciences Sector, Canada Centre for Remote Sensing	Provides links to: • The Atlas of Canada (general Canada-wide maps) • The geodesic survey division (spatial referencing information and databases) • Information on climate change and northern development.	**Atlas of Canada** (home page): http://atlas.nrcan.gc.ca/site/english/index.html **Canadian spatial reference system:** www.geod.nrcan.gc.ca/index_e.php **Canada Centre for Remote Sensing:** www.ccrs.nrcan.gc.ca/index_e.php	Natural Resources Canada Canada Centre for Remote Sensing 588 Booth Street Ottawa, ON K1A 0Y7 Tel: 613-995-0947
Land use	Community watersheds and maps	1995–present	British Columbia	Ministry of Environment, Water Stewardship Division, Science and Information Branch	Locates community watersheds by forest district, location, source, and other parameters. Maps of watersheds available.	**Water Stewardship Division home:** www.env.gov.bc.ca/wsd/data_searches/index.html	Ministry of Environment Science and Information Branch Water Stewardship Division PO Box 9358, Stn Prov Govt Victoria, BC V8W 9M2
Monitoring	Monitoring methods (fish habitat, water quality, lake, groundwater, estuary, ecosystems), measurements, and mapping standards	Various	British Columbia	Ministry of Agriculture and Lands, Integrated Land Management Bureau, Resources Information Standards Committee	Provincially approved standards and methods for monitoring: • aquatic resources (fish habitat, water quality, sediment fish species keys, biological sampling, lake sampling) • earth sciences (groundwater, terrain) • coastal ecosystems (estuary mapping) • terrestrial ecosystems (amphibians, etc.) • other (GPS standards, map projections).	**Resources Information Standards Committee:** www.ilmb.gov.bc.ca/risc/index.html	Publications Co-ordinator Ministry of Agriculture and Lands Corporate Operations Integrated Land Management Bureau PO Box 9365, Stn Prov Govt Victoria, BC V8W 9M3
Organization, Riparian	Reports (monitoring) and web links	1996–present	British Columbia	The Pacific Streamkeepers Federation	Volunteers committed to protecting and restoring aquatic habitats in province.	**The Pacific Streamkeepers Federation:** www.pskf.ca/	The Pacific Streamkeepers Federation 1858 Beaulynn Place North Vancouver, BC V7J 2T1 Tel: 604-986-5059 pskf@direct.ca

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Organization, Extension	Newsletter, web links, and bibliography (water quality)	1998–present	British Columbia	FORREX, Watershed Management Extension Program	FORREX publishes a newsletter (*Streamline*), online articles, and a forest water quality bibliography containing over 800 articles sorted by topic.	**Streamline:** www.forrex.org/streamline/ **Water quality bibliography:** www.forrex.org/program/water/wmbib.asp **FORREX watershed management:** www.forrex.org/program/water/clust_watershed.asp	FORREX Head Office Suite 400, 235 1st Avenue Kamloops, BC V2C 3J4 Tel: 250-371-3746 society@forrex.org
Organization, Sustainability	Trade shows, publications (groundwater, wells, aquifers), lists of suppliers, and legislation	1970–present	British Columbia	BC Ground Water Association	Provincial association to promote sustainable groundwater guidelines and strategies.	**BC Ground Water Association**: www.bcgwa.org/	BC Ground Water Association 1708–197A Street Langley, BC V2Z 1K2 Tel: 604-530-8934 secretary@bcgwa.org
Organization, Hydrology, Water quality	Journal, publications (water supply, water quality, hydrology) conferences, newsletter, and bookstore	1976–present	Canada	Canadian Water Resources Association	National organization interested in management of Canada's water resources. Co-ordinates conferences, publishes a journal (*Canadian Water Resources Journal*) and a newsletter (*Water News*), and operates a bookstore.	**Canadian Water Resources Journal** (2004– online): http://pubservices.nrc-cnrc.ca/rp-ps/journalDetail.jsp?jcode=cwrj&lang=eng **Canadian Water Resources Association:** www.cwra.org/default.aspx	CWRA Membership Services 280 Albert Street, Suite 900 Ottawa, ON K1P 5G8 Tel: 613-237-9363 services@AIC.ca
Organization, Water quality	Journal (pollutants, surface water, groundwater, organisms, conservation), conferences, and web links	1967–present	Canada	Canadian Association on Water Quality	Publishes a journal (*Water Quality Research Journal*) with a cost to access, and organizes conferences focussed on water quality.	**Canadian Association on Water Quality**: www.cawq.ca/	Canadian Association on Water Quality PO Box 5050 Burlington, ON L7R 4A6 Tel: 905-336-6291
Organization, Engineering	Conferences, proceedings (water supplies, floods, design of hydraulic structures and distribution systems) and web links	1988–present	Canada	Canadian Society for Civil Engineering, Hydrotechnical Division	Division of a national organization involved in development of water supplies. Organizes conferences, publishes proceedings, and provides web links to journals and associations.	**CSCE activities and conferences:** www.csce.ca/Main.aspx?id=61&lang=1	Canadian Society for Civil Engineering Hydrotechnical Division 4920 de Maisonneuve Boulevard, W. #201 Montreal, QC H3Z 1N1 Tel: 514-933-2634

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Organization, Biology	Conferences and publications (reclamation, fish, impacts of development)	1958–present	Canada	Canadian Society of Environmental Biologists	National organization advancing the conservation and management of Canada's natural resources. Publishes proceedings from national and chapter meetings (some available to purchase online).	**CSEB** home page: www.cseb-scbe.org/english.html	Canadian Society of Environmental Biologists National Office PO Box 962, Stn F Toronto, ON M4Y 2N9
Organization, Geography	Newsletter and conferences	1993–present	Canada	Canadian Geophysical Union	National organization dedicated to the aspects of the physical study of Earth and its space environment. Holds meetings and has a newsletter (*Elements*).	**Canadian Geophysical Union** home page: www.cgu-ugc.ca/	University of Calgary Department of Geology and Geophysics CGU Secretariat 2500 University Drive NW Calgary, AB T2N 1N4 Tel: 403-220-2794 cgu@ucalgary.ca
Organization, Sustainability	Trade shows, information for the general public, lists of suppliers, conferences, and legislation	Unknown	Canada	Canadian Ground Water Association	National association to promote sustainable groundwater guidelines and strategies.	**Canadian Ground Water Association:** www.cgwa.org/index.htm	Canadian Ground Water Association 1600 Bedford Highway, Suite 100–409 Bedford, NS B4A 1E8 Tel: 902-845-1885 info@cgwa.ca
Organization, Wetlands	Publications (wetlands, wildlife, habitat), educational information, and migration map	1938–present	Canada	Ducks Unlimited Canada	A wetland and wildlife conservation organization that has 520 projects in British Columbia. Involved in habitat conservation and public education, supporting "the sustainable use and harvest of renewable resources based on sound science."	**Ducks Unlimited Canada:** www.ducks.ca/	Ducks Unlimited Provincial Office 13370–78th Ave, Unit 511 Surrey, BC V3W 0H6 Tel: 604-592-0987 du_surrey@ducks.ca
Organization, Research	Publications (climate change, hydrology), seminars, data sets	2005–present	British Columbia	Pacific Climate Impacts Consortium	Aims to quantify the impacts of climate change and variability on the physical environment in Pacific North America and stimulate collaboration between government, academe, and industry.	**PCIC:** http://pacificclimate.org/	University of Victoria Pacific Climate Impacts Consortium C177 Sedgewick Building PO Box 1700 Sta CSC Victoria, BC V8W 2Y2 climate@uvic.ca

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Organization, Biology	Journals (invertebrates, fish, riparian), educational material, bibliographies (since 1959), and web links	1953–present	Canada, United States	North American Benthological Society	Scientific society focussed on biotic communities of lake and stream bottoms and their role in aquatic ecosystems. Publishes two journals (*Journal of the NABS* and *Bulletin of the NABS*) that require subscription (purchase).	**North American Benthological Society:** www.benthos.org/index.aspx **Publications:** www.benthos.org/Journal-(JNABS).aspx www.benthos.org/other-publications.aspx	North American Benthological Society PO Box 1897 Lawrence, KS 66044-8897 USA webmaster@benthos.org
Research, Fish and ecology	Publications (fish, fish habitats, riparian, streams)	Report summary 1950s–present	British Columbia	Ministry of Environment, Ecosystems Branch	EcoCat, the Ecological Reports Catalogue provides access to digital reports and files. FishInfo BC provides information on fish resource and Internet links, including FishWizard, inventory, and project documentation.	**EcoCat:** www.env.gov.bc.ca/ecocat/ **FishInfo BC:** www.env.gov.bc.ca/fish/fiss/index.html **FishWizard**: www.fishwizard.com/default.htm	Ministry of Environment Ecosystems Branch PO Box 9358, Stn Prov Govt Victoria, BC V8W 9M2
Research, Watersheds	Reports (hydrology, water supply, water quality, forestry practices, wetlands, riparian), watersheds, other research topics, and web links	1930s–present	British Columbia	Ministry of Forests and Range, Forest Stewardship Division, Research Branch	Variety of research programs at the branch and region level including a number of research watersheds (Carnation Creek, Haida Gwaii, Stuart-Takla, Slim-Tumuch, Upper Penticton Creek, Redfish Creek). Regional websites provide summary publications, current research, and links to publications from research watersheds and other research projects with water components.	**Coast Region research group publications:** www.for.gov.bc.ca/rco/research/vanpublicat.htm **Northern Interior Forest Region** (research links): www.for.gov.bc.ca/rni/research/index.htm **Southern Interior Forest Region Forest Science Program:** www.for.gov.bc.ca/rsi/research/index.htm **Fish-Forestry Interaction Research:** www.for.gov.bc.ca/hre/ffip/	Ministry of Forests and Range Research Branch PO Box 9519, Stn Prov Govt Victoria, BC V8W 9C2 Tel: 250-387-6721 Forests.ResearchBranchOffice@gov.bc.ca Also see contact information on individual Forest Region websites

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Research	Reports (hydrology, forest practices, stream ecosystems, riparian, geomorphology, geotechnical and hydrotechnical engineering), journal articles, and current research	1908–present; some older references	British Columbia	University of British Columbia Forest Sciences and Forest Resource Management departments, Department of Geography, Department of Civil Engineering	Numerous researchers and graduate students. Library system contains access and links to many databases, articles, journals, and other resources.	**Department of Forest Resource Management:** www.forestry.ubc.ca/dept/frm/ **Department of Geography:** www.geog.ubc.ca/research/index.html **Civil Engineering:** www.civil.ubc.ca/research.htm	University of British Columbia Faculty of Forestry 2424 Main Mall Vancouver, BC V6T 1Z4 Department of Geography 1984 West Mall Vancouver, BC V6T 1Z2 Dept of Civil Engineering 6250 Applied Science Lane, Room 2010 Vancouver, BC V6T 1Z4
Research	Journals (hydrology, forest practices, fish, fish habitat, riparian, geomorphology, hydrotechnical engineering) and other publications	1901–present; journals online since 1997	Canada	National Research Council of Canada	Publishes a series of journals including: • *Canadian Journal of Civil Engineering* (since 1973) • *Canadian Journal of Earth Sciences* (since 1963) • *Canadian Journal of Fisheries and Aquatic Sciences* (since 1901) • *Canadian Journal of Forest Research* (since 1971). Online material is freely available. Also publishes monographs, conference proceedings, and other books.	**Select a journal:** http://pubs.nrc-cnrc.gc.ca/cgi-bin/rp/rp2_jour_e **NRC Research Press:** http://pubs.nrc-cnrc.gc.ca/	National Research Council of Canada NRC Research Press Ottawa, ON K1A 0R6 Tel: 613-993-0362 pubs@nrc-cnrc.gc.ca
Research, Fisheries and fish habitat	Publications (fish, fish habitat, forest practices, impacts of development) and other literature (fisheries, aquatic science, nautical science)	Online 1993–present	Canada	Fisheries and Oceans Canada (formerly Department of Fisheries and Oceans), Science and Research, Freshwater and Marine Habitats	Conducts research on anadromous fish and fish habitat. Site includes summary of ongoing research projects and a publications list. Searchable database accessing the 12 regional libraries across Canada for published and unpublished literature.	**Research programs:** www.pac.dfo-mpo.gc.ca/science/habitats-eng.htm	Fisheries and Oceans Canada B.C. and Yukon Regional Headquarters 200–401 Burrard Street Vancouver, BC V6C 3S4 Tel: 604-666-0384 info@dfo-mpo.gc.ca

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Research, Watersheds	Publications (watershed hydrology, streams, riparian, salmonids, monitoring, storm water), bibliographies (riparian, temperature, salmon recovery), and conferences	Online publications 1998–present; bibliographies 1940s–present	United States, Pacific Northwest	University of Washington, The Water Center (formerly Center for Water and Watershed Studies)	Searchable bibliographies including: • Riparian • Temperature effects • Type 5 streams • *Endangered Species Act* salmon recovery library and database.	**Bibliographies:** http://depts.washington.edu/cwws/Outreach/Resources/bibliographies.html **The Water Center:** http://depts.washington.edu/cwws/Outreach/outreach.html	University of Washington The Water Center Box 352100 Seattle, WA 98195–2100 USA Tel: 206-543-6920 cwws@u.washington.edu
Research, Forestry	Publications (watershed hydrology, aquatic habitat)	1976–present	United States, Pacific Northwest	Oregon State University, College of Forestry, Department of Forest Ecosystems and Society	Ongoing research on coastal and interior areas. Collaborative research with university departments and the U.S. Department of Agriculture Forest Service. Projects include: • Watershed process group focussed on steep forested landscapes • CLAMS – watershed processes and aquatic habitat.	**Corvallis Forestry Research Community, research projects:** www.fsl.orst.edu **Watershed Processes Group:** www.fsl.orst.edu/wpg/ **Coastal Landscape Analysis and Modeling Study**: www.fsl.orst.edu/clams/	Oregon State University Department of Forest Ecosystems and Society 321 Richardson Hall Corvallis, OR 97331 USA Tel: 541-737-2244
Research, Riparian and watershed	Reports (watershed hydrology, streams, water supply, water quality), professional aids, and educational material	Online 1995–present	United States	U.S. Department of Agriculture, Forest Service	Stream Systems Technology Center, focusses on stream systems and watershed hydrology. Site includes research publications, training, operational tools, and technology transfer. Has a searchable database of research publications.	**Stream Systems Technology Center:** www.stream.fs.fed.us/index.html **Publications:** www.fs.fed.us/publications/	U.S. Department of Agriculture Forest Service Rocky Mountain Research Station Stream Systems Technology Center 2150 Centre Avenue. Bldg. A, Suite 368 Fort Collins, CO 80526, USA Tel: 970-295-5983 rmrs_stream@fs.fed.us
Research, Water	Publications (groundwater, river hydraulics, sediment transport, reservoirs, water supply), software, and courses	1964–present	United States	U.S. Army Corps of Engineers, Institute for Water Resources	Specialty areas include: • Hydrologic Engineering Center with technical expertise in surface and groundwater, river hydraulics, sediment transport, reservoirs, and real-time water control • Water Use: forecasting and water conservation.	**Hydrologic Engineering Center:** www.hec.usace.army.mil/ **Institute for Water Resources:** www.iwr.usace.army.mil/	U.S. Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center 609 Second Street Davis, CA 95616–4687, USA Tel: 530-756-1104 Webmaster-HEC@usace.army.mil

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Research, Climate, Water	Information on streamflow, precipitation, groundwater, publications (groundwater, surface water, water quality, water use), software, maps, and bibliographies	1879–present	United States	U.S. Geological Survey, Water Resources Division	National research program and water programs have 1.5 million stations.	**Water resources of the United States:** http://water.usgs.gov/index.html **Real-time data:** http://waterdata.usgs.gov/nwis/rt	U.S. Geological Survey Water Science Center Office 934 Broadway, Suite 300 Tacoma, WA 98402, USA Tel: 253-552-1600
Research	Publications (water resources) and journals (hydrology, water research)	1963–present	World	Elsevier B.V.	Publisher of journals and scientific books including: • *Advances in Water Resources* (1979–) • *Journal of Hydrology* (1963–) • *Water Research* (1967–).	**Elsevier B.V.** (home page): www.elsevier.com	Elsevier Journals Customer Service Department 3251 Riverport Lane Maryland Heights, MO 63043, USA Tel: 800-545-2522
Water, Climate	Precipitation, air temperature, hourly lake levels, hourly stream levels/flows, and snow water equivalents	Online is current; historical ~1960s	British Columbia	BC Hydro	Reservoir and Hydromet data: automated data collection stations in or near reservoir systems: • across province (over 100 stations) • Columbia River (seven basins) • Lower Mainland/Interior (nine basins) • Peace River (one basin) • Vancouver Island (four basins).	**Reservoir and Hydromet data** (current): www.bchydro.com/about/our_system/hydrometric_data.html Historical data available from headquarters.	BC Hydro 6911 Southpoint Drive Burnaby, BC V3N 4X8 Tel: 604-224-9376
Water, Groundwater	Groundwater levels, groundwater quality, bedrock lithology, educational material, publications (groundwater, aquifers), and web links	1961–present	British Columbia	Ministry of Environment, Water Stewardship Division	Groundwater conditions in 56 wells monitoring bedrock aquifers and 109 wells monitoring unconsolidated sand and gravel. Groundwater home page provides database links, reference library, lists of contacts, legislation, and issues.	**Groundwater** (home page): www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/index.html	Ministry of Environment Water Stewardship Division Groundwater Section PO Box 9362, Stn Prov Govt Victoria, BC V8W 9M1 GroundWater@gov.bc.ca
Water, Aquifers	Aquifers and maps (electronic resource only)	1994–present	British Columbia	Ministry of Environment, Water Stewardship Division, Watershed and Aquifer Science	Aquifer classification system and database providing mapped locations, delineation of over 600 aquifers, and data query option.	**Aquifers in British Columbia:** www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/	Ministry of Environment Water Stewardship Division Groundwater Section PO Box 9362, Stn Prov Govt Victoria, BC V8W 9M1 GroundWater@gov.bc.ca

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Water, Flood-plains	Floodplain maps and associated design briefs	1984–present	British Columbia	Ministry of Environment, Environmental Protection Division	Floodplain mapping of over 110 rivers and more than 10 lakes. Note: this project terminated in 2003, so there is no direct contact or updating at present.	**Canada – British Columbia floodplain mapping program:** www.env.gov.bc.ca/wsd/data_searches/fpm/index.html	Ministry of Environment Water Stewardship Division PO Box 9358, Stn Prov Govt Victoria, BC V8W 9M2 waterinfo@victoria1.gov.bc.ca
Water, Water quality	Streamflow and water-level data and software packages	1908–present	Canada	Environment Canada, Water Survey of Canada	National Surface Water Data (HYDAT) surface water quantity data (daily, monthly, and instantaneous) for over 2900 active stations and 5100 discontinued sites. CD-ROM of data and analysis software can be ordered.	**Data products and services:** www.wateroffice.ec.gc.ca/index_e.html	Water Survey of Canada Pacific and Yukon Lynne Campo Tel: 604-664-9324 Lynne.Campo@ec.gc.ca
Water quality	Water quality data reports, guidelines, publications (water quality, aquatic life, sediment, monitoring), and legislation	1979–present	British Columbia	Ministry of Environment, Environmental Protection Division	Water quality reports, legislation, and policy; also area-specific reports.	**Water quality:** www.env.gov.bc.ca/wat/wq/index.html	Ministry of Environment Environmental Protection Division PO Box 9339, Stn Prov Govt Victoria, BC V8W 9M1 Tel: 250-387-1288 envprotdiv@Victoria1.gov.bc.ca
Water quality	Legislation, water testing suppliers, and publications (drinking water, sanitation, sewage disposal)	1999–present	British Columbia	Ministry of Health, Environmental Health Protection	Drinking Water Program: lists legislation, approved water testing laboratories, and information on drinking water.	**Public Health Protection, Drinking Water Program:** www.hls.gov.bc.ca/protect/dw_index.html	Ministry of Health Environmental Health Protection 4–2 1515 Blanshard Street Victoria, BC V8W 3C8 Tel: 250-952-1469 HP-PHW@gov.bc.ca
Water quality	Reports (acid rain, pesticides, restoration, groundwater, waste water, climate change) and seminars	1967–present	Canada	Environment Canada, The National Water Research Institute	Canada's freshwater research facility with two main centres in Ontario and Saskatchewan.	**The National Water Research Institute:** www.nwri.ca/nwri-e.html	Environment Canada National Water Research Institute 867 Lakeshore Road PO Box 5050 Burlington, ON L7R 4A6 S&TLiaison@ec.gc.ca

Category	Types of data	Years produced	Geographic region	Agency	Description	Data location, website title, current URL	Contact
Water quality, Monitoring	Publications (monitoring, standards, restoration, testing, groundwater, drinking water, wastewater, wetlands, watersheds)	1970–present	United States	U.S. Environmental Protection Agency	Federal agency that provides monitoring protocols, standards, management and restoration practices, and testing methods. ECOTOX is a database of single chemical toxicity information for aquatic and terrestrial life.	**U.S. Environmental Protection Agency, water:** www.epa.gov/water/ **ECOTOX database:** www.epa.gov/ecotox/	U.S. Environmental Protection Agency Office of Water (4101M) 1200 Pennsylvania Avenue NW Washington, DC 20460, USA OW-GENERAL@epa.gov ECOTOX support: Tel: 218-529-5225 ecotox.support@epa.gov
Water use	Water licence registry and maps	1960s–present	British Columbia	Ministry of Environment, Water Stewardship Division	Water Licences Query: searches by stream, watershed, licence number, and other parameters for existing water licences.	**Water licence web query:** http://a100.gov.bc.ca/pub/wtrwhse/water_licences.input	Ministry of Environment Water Stewardship Division PO Box 9358, Stn Prov Govt Victoria, BC V8W 9M2 Water.Stewardship@gov.bc.ca
Water use	Publications (water licences, water users), legislation, and web links	1983–present	British Columbia	Ministry of Environment, Water Stewardship Division	Information on water legislation, licences, water users. Links to water-rights websites.	**Water-rights information:** www.env.gov.bc.ca/wsd/water_rights/licence_application/index.html	Ministry of Environment Water Stewardship Division PO Box 9358, Stn Prov Govt Victoria, BC V8W 9M2 Water.Stewardship@gov.bc.ca
Water use	Water use, water pricing, water works, and water treatment facilities	1975–2001	Canada	Environment Canada	Water use data include municipal water use for 1200 municipalities with populations over 1000. Industrial water use compiled from six surveys.	**Water use data:** www.ec.gc.ca/eau-water/	Environment Canada Inquiry Centre 351 St. Joseph Boulevard 7-PVM Gatineau, QC K1A OH3 Tel: 800-668-6767 enviroinfo@ec.gc.ca

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