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Sediment production following severe wildfire and post-fire salvage logging in the Rocky Mountain headwaters of the Oldman River Basin, Alberta

Uldis Silins [a], Micheal Stone [b,*], Monica B. Emelko [c], Kevin D. Bladon [a]

[a] Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada T6G 2H1
[b] School of Planning and Department of Geography, University of Waterloo, Waterloo, Canada N2L 3G1
[c] Department of Civil and Environmental Engineering, University of Waterloo, Waterloo, Canada N2L 3G1

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ABSTRACT

In 2003, the Lost Creek fire burned 21,000 ha of nearly contiguous crown land forests in the headwater regions of the Oldman River Basin, Alberta. Seven small watersheds with various levels of land disturbance (burned, post-fire salvage logged, unburned) were instrumented and monitored for four years to measure stream discharge, sediment concentration, and sediment yields for a range of dominant flow periods characteristic of the region (baseflow, spring melt, and stormflow). Stream discharges reflected runoff regimes consistent with high regional precipitation and the high relief physiographic setting of the study area. Suspended sediment concentrations and yields were significantly higher in both burned and post-fire salvage logged watersheds than in unburned watersheds and were strongly influenced by topographic and hydro-climatic controls. Sediment availability was much higher in both the burned and post-fire salvage logged watersheds but it varied strongly with flow condition, particularly during the snowmelt freshet and high flow events. Because of increases in wildfire frequency and severity over recent decades, understanding the range of impacts from both wildfire and post-disturbance management strategies such as salvage logging is likely to become increasingly important for land managers.

1. Introduction

Wildfires are a major source of disturbance in forested watersheds. Although they are highly variable in severity and spatial extent, wildfires can significantly alter a range of physical and biogeochemical processes that influence both source water quality and quantity (Shakesby and Doerr, 2006). Moreover, the disturbance effects from severe wildfires can exceed the impacts typically observed after man-made disturbances, such as commercial forest harvesting (Carignan et al., 2000). In recent decades, more frequent and severe landscape fires have been reported in many North American forested regions and have been attributed to warmer spring and summer temperatures (Westerling et al., 2006).

Wildfires alter watershed behaviour by affecting several key hydrological processes. In the short term (<1 year post-fire), temporary water repellent soil layers resulting from wildfire reduce infiltration capacity, thereby increasing runoff relative to pre-burn conditions via overland flow (DeBano, 2000; Benavides-Solorio and MacDonald, 2001). As a result, in response to precipitation events, peak stream discharge often increases with shortened response times (Moody and Martin, 2001; Neary et al., 2003; Kunze and Stednick, 2006; Moody et al., 2008a,b). Over longer periods (>1 year post-fire), wildfires result in increased soil moisture because they reduce precipitation, interception, and transpiration from the forest canopy. Consequently, peak flows and overall water yield from burned landscapes increase relative to pre-burn conditions (Kunze and Stednick, 2006; Shakesby and Doerr, 2006; Moody et al., 2008a). Accordingly, wildfires can significantly lower erosion thresholds and increase erosion rates (Benavides-Solorio and MacDonald, 2001), thereby increasing sediment production (Ewing, 1996; Kunze and Stednick, 2006).

Most research describing wildfire effects on hydrology and water quality can be characterized as “opportunistic” post-hoc study of specific responses to individual wildfires that vary in severity and spatial extent; moreover, most of this work has been conducted at plot or hillslope scales. Comparatively fewer watershed-scale studies describing wildfire effects on hydrology and water quality have been conducted and most of these report differential watershed responses from a limited range of hydro-climatic settings. While it is generally understood that post-fire erosion and sediment supply are governed by a range of factors at plot or hillslope scales (e.g. fire severity/extent, sensitivity of the watershed to erosion, precipitation regime, and soils/geology) (Robichaud, 2000; Martin and Moody, 2001), less is known about variation in water quality responses to wildfire at the watershed-scale (Bladon et al., 2008).

* Corresponding author.
E-mail address: mstone@uwaterloo.ca (M. Stone).

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Post-wildfire studies of erosional processes have been conducted in the Rocky Mountain region of western North America (Wondzell and King, 2003); however, the results from these studies are based on multiple wildfires that are variable in burn severity/extent, climate, and physiography. Post-fire land management practices such as salvage logging can contribute additional variability and complicate data interpretation because they impact sediment delivery to streams (DellaSala et al., 2006); these impacts are also poorly documented. As a consequence, post-fire impacts and subsequent recovery in any specific region such as the steep, high water yielding watersheds in sub-humid continental regions of the Rocky Mountain cordillera of Alberta are not well described. That region is particularly relevant in Canada because the watersheds within it form critical source waters for the drinking water supplies of much of the settled central and southern regions of Alberta.

The objectives of the present study were to 1) quantify watershed-scale sediment production (concentration and specific yield) in response to wildfire and post-wildfire land management intervention (i.e. salvage logging) in the high water yielding headwaters of Alberta's southern Rocky Mountains and 2) quantify early watershed-scale recovery of sediment production (if evident) after both types of disturbances.

2. Materials and methods

2.1. Study area

The Lost Creek wildfire burned more than 21,000 ha in the Crowsnest Pass, Rocky Mountain region of south western Alberta (49° 37′ N, 114° 40′ W) during the late summer and fall of 2003. The fire was particularly severe in that it consumed nearly all forest cover and forest floor organic matter across a large proportion of the headwater regions of both the Castle and Crowsnest Rivers (Fig. 1). Seven watersheds were instrumented to examine the effects of wildfire on a range of watershed values, including streamflow and water quality. Initially, three burned watersheds (Lynx Creek, Drum Creek, and South York Creek) and two unburned watersheds (Star Creek and North York Creek) were instrumented in the spring of 2004. Two burned and subsequently salvage logged watersheds were added to the study in early 2005 (Lyons Creek West and Lyons Creek East). Salvage logging in these watersheds began in winter 2003/04 and continued through winter 2004/05.

Forest cover of all seven watersheds was similar before the wildfire. It was characterized by Lodgepole pine (*Pinus contorta* Dougl. ex Loud.

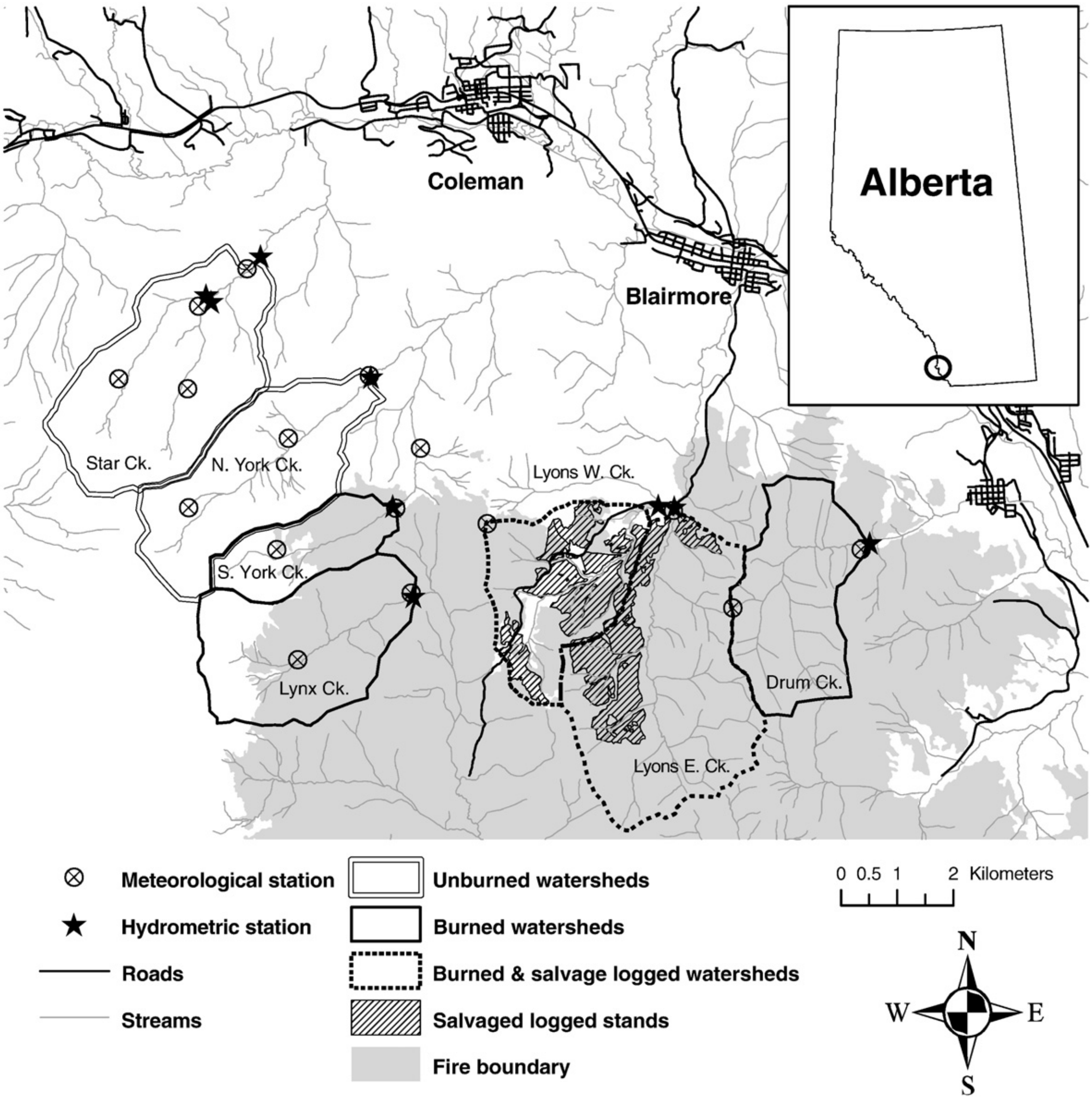

Fig. 1. Map of the Southern Rockies Watershed Project study area showing the 2003 Lost Creek fire boundary, study watersheds, hydrometric gauging stations, and meteorological stations.

var. *latifolia* Engelm.) dominated forest at lower elevations, subalpine forest at mid elevations dominated by Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt), with alpine ecozones at higher elevations characterized by alpine meadow vegetation and bare rock extending above tree line. Soils throughout the study area were well to imperfectly drained (Eutric or Dystric Brunisols) with weak horizon development (characteristic of higher elevation northern environments).

The areal extent of burn and physical characteristics (mean elevation, watershed slope and channel slope) of the study area are listed in Table 1. Forests within the burned and burned–salvage logged watersheds were nearly 100% consumed in the wildfire. The proportion of total watershed area burned in the fire varied from 53 to 100% among study watersheds; alpine areas (above tree line) did not have adequate fuel to sustain the fire and thus these areas did not burn.

2.2. Hydrometric and sediment instrumentation

Hydrometric and sediment monitoring stations were located at the outlet of each of the seven study basins (Fig. 1). A multi-level hydrometric and sediment sampling program was employed to balance measurement of climate, streamflow, and water quality while optimizing the logistical and financial constraints of working in this remote environment at the watershed-scale.

Instantaneous stream discharge was measured using standard area–velocity current metering techniques with a Swoffer (Model 2100) velocity meter. Water levels were simultaneously measured using staff gauges to develop stage–discharge relationships. Continuous stage measurements were collected with gas bubblers (Waterlog model H-350) or pressure transducers (Onset model U-20). Using discharge hydrographs and precipitation data, regional streamflow regimes were categorized into three dominant flow periods: 1) baseflow or non-event (summer and winter), 2) snowmelt freshet and 3) stormflow, resulting from rainfall in each watershed. Hourly temperature, relative humidity, and precipitation were recorded from fifteen meteorological stations that were located throughout the study watersheds (Fig. 1).

The sampling strategy for total suspended sediment (TSS) production involved collection of two independent (overlapping) data sets. The first data set was collected using manual sampling beginning in early spring of 2004 and consisted of instantaneous discharge and suspended sediment measurements every 10 days during snowmelt freshet, every 14 days after the freshet during the ice-free periods and approximately every 1 to 2 months during winter. Suspended solids were collected using depth integrated grab sampling in 1-l acid washed Nalgene bottles. Collection of a second, continuous data set using automated sampling began in the spring of 2005. Isco automated water samplers (Teledyne Isco Inc. Lincoln, NE, U.S.A.) were used to collect composite daily TSS samples, consisting of 4–250 ml sub-samples collected every 6 h during ice-free periods from May to October in a sub-set of unburned (Star Creek), burned (South York and Drum Creek) and salvage logged (Lyons Creek East) watersheds.

For both data sets, sediment concentration (mg l^{-1}) was determined using standard filtration-gravimetric methods (Stednick, 1991). Specific sediment yield (kg ha^{-1} day^{-1}) was calculated from the product of measured instantaneous (manual samples) or mean daily (automated samples) TSS concentration and discharge on an equivalent area basis for each watershed.

2.3. Statistical analyses

Because of the random nature of wildfires, the lack of pre-burn hydro-climatic data limits most landscape scale wildfire-watershed research to post-hoc description of differences in watershed behaviour between burned and representative unburned, unburned watersheds. In this context, our results were interpreted cautiously and spatial and temporal inferences were limited to generally similar hydro-climatic settings. While the seven research watersheds do encompass an overlapping range of physiographic and hydro-climatic settings, they are all representative of steep, high water yielding watersheds of southern Alberta's Rocky Mountains. Thus, we considered all seven as part of the same “population” of front-range watersheds. All data analyses were performed with the SAS statistical package (Version 9.1, SAS Institute Inc., Carey, NC).

Sediment concentration and yield were not normally distributed (Shapiro–Wilk test), thus a series of single factor Kruskal–Wallis tests and Dunn's mean comparison tests were used to analyze the effects of the watershed groups (unburned, burned, salvage logged) and time (years elapsed since the fire) on sediment production. Sediment discharge relationships were developed using least-squares linear regression and compared among watershed groups using an overall test for coincidental regression (Zar, 1999).

3. Results

3.1. Precipitation and stream discharge

The average annual precipitation across the seven watersheds during the period from 2004 to 2007 was 1078 mm (Table 2). The greatest precipitation occurred in the higher elevation Flathead Range watersheds along the western portion of the study region (i.e. Star, North York, South York, and Lynx Creek) and the majority of the total annual precipitation (50 to 70%) fell as snow from October to April. Removal of the forest canopy by wildfire in the burned and post-fire salvage logged watersheds increased the snow water equivalents by a factor of 2 to 3 compared to the unburned watersheds (data not shown). Over the first four post-fire growing seasons, meteorological conditions varied considerably. The first post-burn season of 2004 was cool and moist, but generally without large precipitation events in summer (0.1–5 mm day^{-1} for 55% of days in the growing season). The

Table 1
Physical characteristics of the study watersheds.

	Area (ha)	Burned (ha,%)	Salvage logged (ha, %)	Elevation (mean/range; m)	Catchment slope (%)	Channel slope (%)
Unburned						
Star	1059	0 (0)		1851 (1479–2627)	45.0	10.5
North York	829	2 (0.2)		1931 (1562–2633)	48.8	14.8
Burned						
South York	359	191 (53)		1971 (1691–2635)	42.1	8.3
Lynx	821	553 (67)		1906 (1632–2629)	43.3	5.9
Drum	713	712 (100)		1731 (1432–2156)	47.5	9.3
Burned and salvage logged						
Lyons (East)	1315	1072 (82)	262 (20)	1685 (1441–2027)	31.8	5.0
Lyons (West)	707	413 (58)	238 (34)	1666 (1449–2059)	24.8	7.2

Table 2
Mean annual precipitation and streamflow of unburned, ($n=2$), burned ($n=3$), and post-fire salvage logged ($n=2$) watersheds.

	2004	2005	2006	2007
Precipitation (mm year^{-1})				
Unburned	1264	1321	872	877
Burned	1106	1455	1003	965
Salvage logged		1097	1017	661
Streamflow (mm year^{-1})				
Unburned	663	1001	598	571
Burned	871	1003	761	760
Salvage logged		682	535	478

second post-burn season (2005) was notable for several extremely large rainfall events in June (~150–175 mm of rain over 8 days). These events saturated soils and resulted in elevated streamflow responses to smaller subsequent precipitation events throughout the remainder of the month. The third and fourth post-burn seasons (2006 and 2007) were very dry with no measurable precipitation observed from early June until mid or late September.

Stream discharges in the study area were characteristic of very high water yielding Rocky Mountain streams (Table 2). Spring snowmelt (approximately mid-March until early June) generally produced the highest continuous streamflows (mean daily discharges of ~5–10 mm day^{-1}). Variation in watershed elevation among study watersheds produced notable differences in the timing of the melt period among watersheds, however. The snowmelt freshet in the higher elevation watersheds of the Flathead Range typically occurred from early May to mid-June, while the melt freshet occurred much earlier (from late March to end of April) in the Blairmore Range watersheds (Lyons E., Lyons W., and Drum Creek). All streams in the study area responded quickly to rain events, primarily due to their steep relief. Storm hydrographs were characterized by rapid time to rise and steep post-peak flow recession limbs. Baseflows in late summer and the over winter period were generally near 0.5–2 mm day^{-1}. Rain-on-snow or mid-winter melt events were a common occurrence, producing some of the larger flows, with mean daily discharge in excess of 30 mm day^{-1}. While the heavy rains in June 2005 produced very high discharges, no severe post-fire flooding was observed.

3.2. Sediment concentration and yield — manual sampling (2004–2007)

Total suspended sediment (TSS) concentration and yield were strongly associated with disturbance levels. The magnitude of sediment transport varied with time after the wildfire (Fig. 2). The highest TSS concentrations were observed in burned and post-fire salvage logged watersheds. Compared to the unburned watersheds, TSS concentrations and yields across the four post-fire years were 8-times greater in the burned ($p<0.01$) and 9-times greater in the salvage logged watersheds ($p<0.01$). However, differences in mean TSS concentrations ($p=0.94$) or sediment yield ($p=0.14$) were not observed between burned and the salvage logged watersheds during this same period. In the four post-fire years, the mean TSS concentration in the unburned watersheds was 2.7 mg l$^{-1}\pm$0.7 (S.E.), compared to 21.9 mg l$^{-1}\pm$7.6 and 23.1 mg l$^{-1}\pm$5.4 in the burned and salvage logged watersheds, respectively. Compared to the unburned streams, mean annual TSS concentrations over the 2004 to 2007 study period were 3.8- to 11.0-times higher in burned streams and 1.3- to 10.9-times higher in post-fire salvage logged streams. Similarly, mean TSS yields during the study period were 0.3 kg ha^{-1} day$^{-1}\pm$0.2 (S.E.) in the unburned watersheds, compared to 2.1 kg ha^{-1} day$^{-1}\pm$0.9 in the burned and 2.1 kg ha^{-1} day$^{-1}\pm$0.8 in the salvage logged watersheds. During the 2004 to 2007 study period, mean annual TSS yields in burned and post-fire salvage logged watersheds were respectively 2.7- to 14.3-times higher and 0.7- to 20.4-times higher in than in unburned watersheds.

Concentrations of TSS were significantly higher in burned watersheds compared to unburned watersheds in 2004 ($p<0.001$), 2005

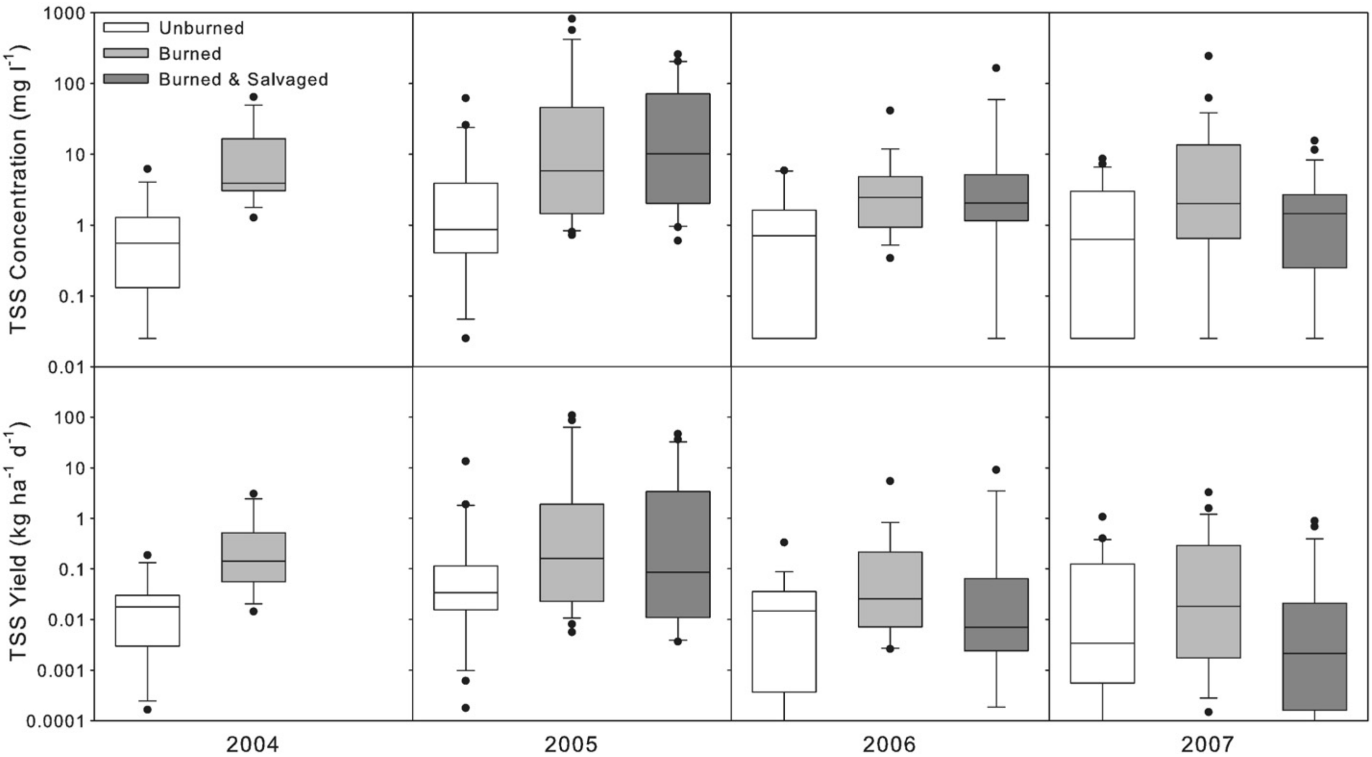

Fig. 2. Box-and-whisker plots of annual total suspended sediment (TSS) concentration (mg l^{-1}), and annual TSS specific yield (kg ha l^{-1} day l^{-1}) for unburned, burned, and salvage logged watersheds from 2004 to 2007.

($p<0.01$), 2006 ($p<0.01$), and 2007 ($p=0.04$) (Fig. 2). The TSS concentrations were higher in the salvage logged watersheds compared to unburned watersheds in 2005 ($p<0.01$) and 2006 ($p<0.01$), but not in 2007 ($p=0.28$). Mean TSS concentrations were greater from salvage logging than burned watersheds alone during the very wet year of 2005 ($p=0.04$), but no significant differences in mean TSS concentrations were evident in these watershed groups during the dry summers of 2006 ($p=0.54$) and 2007 ($p=0.28$). The largest differences in sediment production between undisturbed and disturbed landscapes were observed during the snowmelt freshet and periodic stormflows, however significant effects of wildfire and salvage logging were still evident during lower flows (non-event periods). During higher flow periods (snowmelt freshet and stormflows), mean TSS concentrations in disturbed watersheds were 2- to 100-times higher than in undisturbed watersheds during the 2004 to 2007 study period. Averaged across the four years since the burn, TSS concentrations in burned watersheds were 7-times greater during snowmelt, 11-times greater during storm events and 2-times greater during baseflow periods than in unburned watersheds. Mean TSS concentrations in salvage logged watersheds were 24-times greater during snowmelt periods, 7-times greater during stormflows, and 2-times greater during baseflow periods compared to unburned watersheds.

A comparison of mean TSS concentration and discharge relationships between unburned, burned and post-fire salvage logged watersheds provides additional insight into sediment production in the watershed groups across a range of streamflows (Fig. 3). While greater TSS concentrations were observed at higher streamflows in all watershed groups, there were significant differences in the slopes and intercepts of the discharge and TSS relationship between burned and unburned basins for the initial two years (2004 and 2005) after the fire ($p<0.001$). Differences in these parameters were not statistically significant during the drier seasons of 2006 ($p=0.06$) and 2007 ($p=0.11$). Similarly, higher TSS concentrations were evident in post-fire salvage logged watersheds compared to unburned basins across a range of stream discharges in 2005 ($p<0.001$) and 2006 ($p=0.01$), but not in 2007 ($p=0.06$). The data appear to suggest that higher TSS concentrations were produced at any given discharge in the salvage logged watersheds compared to the burned watersheds (Fig. 3); however, these were not statistically significant in any of the years from 2005 to 2007 ($p=0.12$ to 0.21).

3.3. Sediment concentration and yield — continuous seasonal sampling (2005–2007)

Continuous TSS and streamflow data (ice-free season) provide additional insight into differences in timing of sediment production in a sub-set of study watersheds during the second, third, and fourth summer seasons after the burn (Fig. 4). Sediment production in the unburned (Star Creek), burned (South York and Drum Creek) and salvage logged (Lyons East Creek) watersheds was clearly related to seasonal streamflow regime. The highest sediment concentrations observed during the 2004 to 2007 study period were measured during early summer melt periods or in response to periodic stormflow events. Sediment production was higher during the high precipitation year of 2005 than the relatively lower precipitation years of 2006 and 2007. Several factors including precipitation intensity, magnitude, and antecedent moisture conditions impacted TSS concentrations during storm events and resulted in considerable variability in these data. Nonetheless, TSS concentrations were generally higher in burned and post-fire salvage logged watersheds than in the unburned watershed. Although no precipitation generated runoff was measured from mid-June to early September in 2006 and 2007, the median TSS concentrations in disturbed watersheds generally remained 2- to 3-times greater than in the unburned watershed (Fig. 4). The highest annual sediment concentrations and yields were observed during the snowmelt freshet,

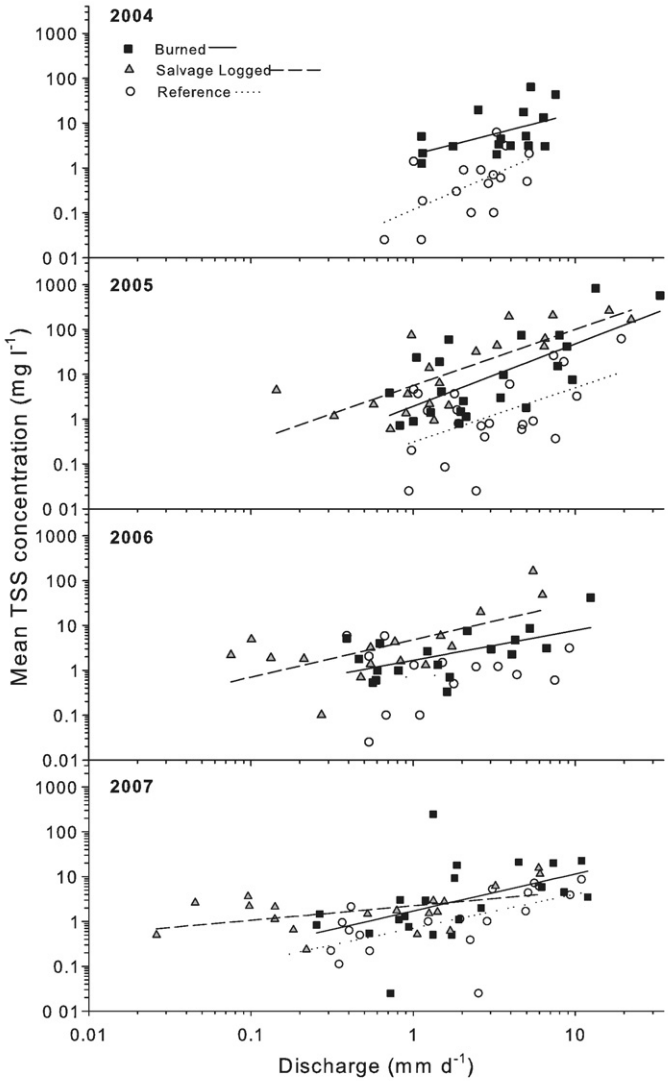

Fig. 3. Relationship between mean total suspended sediment (TSS) concentration (mg l^{-1}) and instantaneous discharge (mm day^{-1}) for unburned, burned, and salvage logged watersheds from 2004 to 2007.

which occurred in late May in the two higher elevation watersheds situated in the Flathead Range (Star and S. York Creek). In contrast, peak melt freshet discharges typically occurred in mid-late April in the lower elevation watersheds of the Blairmore Range (Lyons E. and Drum Creek) when freezing overnight temperatures and site access limitations precluded capturing this data with automated sampling. Thus, only the peak or immediate post-peak melt was sampled in these latter two watersheds.

Differences in cumulative total specific sediment yields (kg ha^{-1}) in the continuously sampled watersheds are presented in Fig. 5. During the high precipitation year of 2005, sediment yields in the two burned and one salvage logged watersheds were 10- to 35-times higher than in the unburned watershed (Star Creek). No measurable precipitation was observed from early June until mid-late September in 2006; consequently, sediment production primarily occurred during spring freshet and a few storms in May. With the exception of South York Creek, sediment yields in Lyons and Drum Creeks during the dry summers of 2006 and 2007 were comparable to Star Creek. The comparatively high sediment yields in South York Creek in 2007 were associated with its steep and moist hydro-climatic setting. In addition to having the highest valley gradient and channel slope (Table 1), South York Creek received the highest annual precipitation

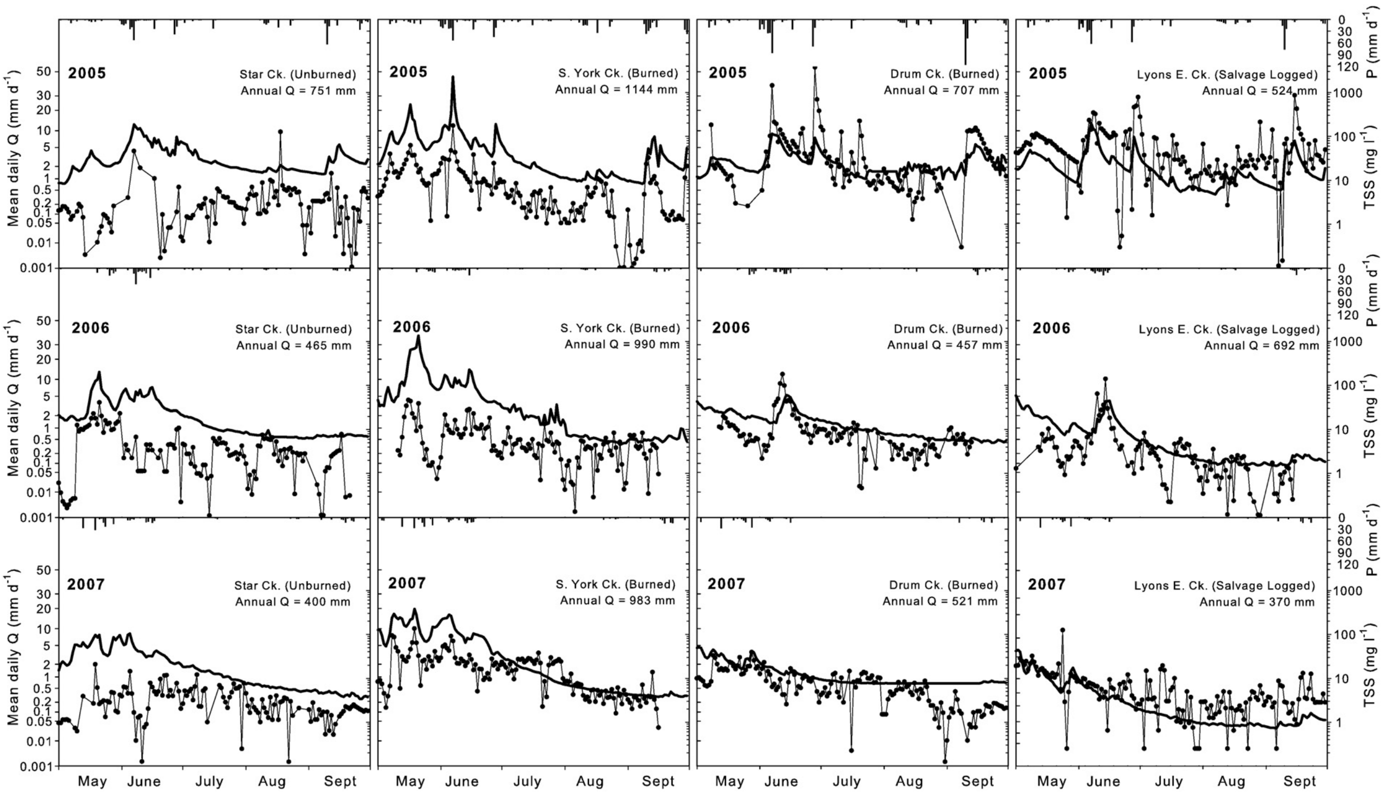

Fig. 4. Time series of total daily precipitation (mm), mean daily discharge (mm day^{-1}), and mean daily total suspended sediment (TSS) concentration (mg l^{-1}) from May 1 to Sept. 30 for watersheds instrumented with ISCO automated samplers during 2005 to 2007. Total annual water yield (mm year^{-1}) is indicated for each watershed. Thick line indicates mean daily discharge, and thin line with symbols indicates mean daily TSS concentration.

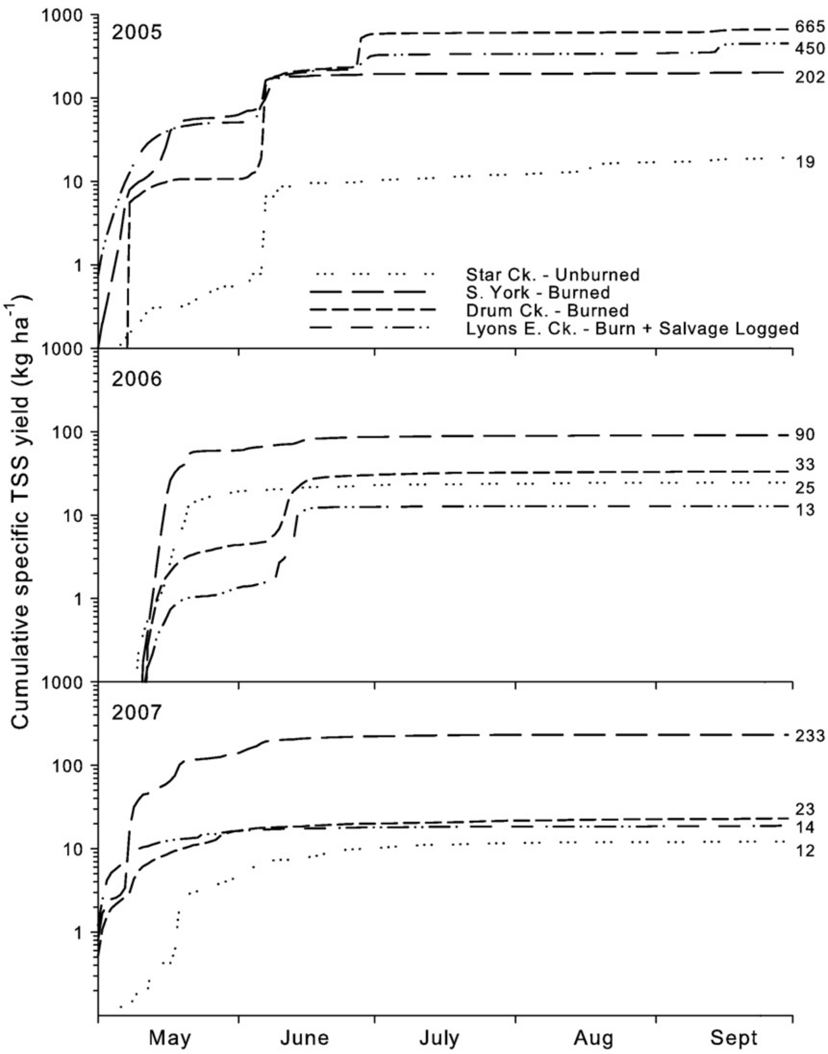

Fig. 5. Cumulative total suspended sediment (TSS) specific yield (kg ha^{-1}) from May 1 to Sept. 30 for watersheds instrumented with ISCO automated samplers during 2005 to 2007. Numbers on figures reflect accumulated TSS specific yield on Sept. 30.

(1471–1185 mm year^{-1}) and produced the highest recorded flow (1144–983 mm year^{-1}) from 2005 to 2007.

4. Discussion

4.1. Suspended sediment concentrations and yields

During the four years after the Lost Creek wildfire in the Rocky Mountain headwaters of the Oldman River Basin in Alberta, the mean annual TSS concentrations and yields were respectively 8- and 9-times higher in burned and post-fire salvage logged watersheds than in unburned watersheds (Fig. 2). While most studies of wildfire impacts on sediment transport have been conducted at plot or hillslope scales, our findings are generally consistent with a smaller number of other watershed-scale studies that report that the timing of peak TSS production (Fig. 3) generally coincides with the highest discharge events (Ewing, 1996; Kunze and Stednick, 2006; Mayor et al., 2007). While the elevated post-fire TSS concentrations and sediment yields we observed in burned watersheds is generally similar to those reported elsewhere (Moody and Martin, 2001; Kunze and Stednick, 2006; Mayor et al., 2007), comparison with other studies should be made cautiously. The relative differences we observed in sediment concentration and yields between burned and salvage logged watersheds with unburned watersheds were of similar or greater magnitude than those reported by Helvey (1980), Lane et al. (2006), Mast and Clow (2008), and others. However, comparisons of absolute magnitudes of post-fire sediment production are confounded by variation of factors including climate, geology, geomorphology, watershed sensitivity to erosion, vegetation, fire severity and extent (Robichaud, 2000; Martin and Moody, 2001) as well as variation in how sediment yields and exports have been computed among studies (Lane et al., 2006). Similarly, differences in catchment scale make some comparisons difficult to interpret. For example, while Ewing (1996) reported mean post-fire sediment concentrations in burned watersheds (0.03–821 mg l^{-1}) that were similar in magnitude to those we observed, our contributing watershed areas were over 1000-times smaller.

It is generally acknowledged that post-disturbance salvage logging can result in additional stream sediment production, as the timing of these land management activities typically occurs when forests are most vulnerable to additional impacts or disturbances (DellaSala et al., 2006). The present investigation is one of the few to document the effects of post-fire salvage logging on sediment production. McIver and Starr (2000) reported only four studies worldwide that had examined sediment transport in relation to post-fire salvage logging.

4.2. Effects of wildfire on sediment sources and availability

Although not directly measured in the present study, several changes to sediment availability and hillslope mass wasting processes were directly observed in the burned watersheds. These included sediment redistribution on hillslopes by wind, overland flow, and mass wasting processes such as soil creep and stream bank failures. Post-fire increases in stream discharge coupled with the absence of bank vegetation dramatically altered the morphology of many streams and subsequently reduced bank stability in burned and salvage logged watersheds (Fig. 6). In salvage logged watersheds, sediment redistribution appeared to be further exacerbated by linear features, such as skid-trails and the larger network of trails and roads, which served as conduits for overland flow and sediment transport. The increased availability and down slope movement of sediment in burned and salvage logged watersheds also accelerated sediment transfer and storage in adjacent streams. These observations are consistent with the findings of others who have noted significant post-wildfire changes in soil structure by the formation of temporary water repellent soil layers that reduce infiltration capacity, thereby increasing runoff relative to pre-burn conditions via overland flow (DeBano, 2000; Benavides-Solorio and MacDonald, 2001). These changes have been associated with increased soil erosion rates (Johansen et al., 2001), sediment redistribution by overland flow (Onda et al., 2008), and mass wasting processes (Meyer and Wells, 1997) that ultimately increase the source and availability of sediment transferred to stream channels.

4.3. Recovery

In the present study, significant differences in mean seasonal TSS concentrations and yield were observed within the first two years after the fire, and these differences diminished over time and were generally smaller (though statistically significant) four years after the fire. These outcomes are consistent with several studies of wildfire that have reported differences in sediment regime that have lasted for at least 4 to 6 years post-fire (Helvey, 1980; Beaty, 1994; Ewing, 1996; Mayor et al., 2007). While this temporal pattern of change is generally consistent with the comparatively few watershed-scale studies that have measured post-fire sediment production for periods long enough to adequately estimate the early trajectory of recovery, such estimation of trends in recovery should be approached with caution. Because the majority of watershed-scale studies have assessed the effects of wildfire on sediment production without an unburned reference for comparison (Helvey, 1980; Ewing, 1996; Moody and Martin, 2001; Kunze and Stednick, 2006; Lane et al., 2006; Rulli and Rosso, 2007) comparing our observation on the temporal pattern of recovery in post-fire sediment production (back to pre-fire conditions) with other studies is difficult. Moreover, sediment transport processes operate at a range of temporal scales. While post-fire re-establishment of vegetation that occurs in relatively short time frames (e.g. several years) can be expected to decrease sediment transport to streams via overland flow, mass wasting processes and decreased bank stability resulting from wildfires will continue to deliver sediment from hillslopes to streams (where it can be stored) over relatively longer periods of time (e.g. decades or centuries). Furthermore, the temporal distribution of hydrologic events capable of transporting sediment can affect the observed temporal pattern of sediment production. In a short-term (15 month) study of sediment production after the 2003 McLure wildfire in the nearby central interior of British Columbia (Canada), Petticrew et al. (2006) concluded that there was no major short-term response to the wildfire because of the generally dry conditions during the monitoring period. In contrast, while higher precipitation during the immediate post-fire years (2004 and 2005) produced notably greater sediment production in the present study, we did observe significantly elevated TSS despite the lack of precipitation in early June through September of 2006 and 2007. We interpret this observation as a likely reflection of both the continued delivery of sediment due to wildfire and associated slumping and mass wasting processes (Fig. 6) and redistribution of channel sediments. This notion is generally consistent with the work of Moody and Martin (2001) who estimated that 67% of eroded sediment remained stored in dryer Rocky Mountain watersheds four years after wildfire and estimated catchment-scale sediment residence times of several centuries. Thus, the likely time scales for recovery of post-fire sediment production are in strong contrast to much shorter time frames reported for post-fire nutrient production (Hauer and Spencer, 1998; Bladon et al., 2008; Mast and Clow, 2008) illustrating strongly differential post-fire recovery trajectories for a range of water quality parameters.

5. Conclusions

Important changes in hydrology and the sediment regime of headwater watersheds in the eastern slopes of the Rocky Mountains

Fig. 6. Near channel mass wasting and bank erosion at Lyons East Creek in spring 2005.

(southern Alberta) were associated with both wildfire and post-fire salvage logging. Sediment production increased dramatically in burned and post-fire salvage logged catchments, but were also strongly mediated by topographic and hydro-climatic controls. For example, during the snowmelt freshet (May to June) discharge and the rate of sediment transport were generally higher in burned watersheds situated in the steep gradient Flathead Range catchments compared to the lower elevation Blairmore range catchments. While sediment production in burned watersheds remained elevated four years after the fire, the largest impacts were observed within the first three years of the wildfire. The practice of post-fire salvage logging increases mass wasting and creates more effective terrestrial sediment transport networks to stream channels and produced more sediment than burned watersheds without salvage logging. This type of information is needed to evaluate post-disturbance trade-offs among resource values such as comparative benefit of capturing economic value from salvage logging operations against increased sediment production and associated water quality deterioration associated with such activities. Given the trend for more frequent and severe wildfires in many regions (Gillett et al., 2004; Westerling et al., 2006), these findings may be of particular concern and increasingly important to natural resource managers and for integrated source water management planning.

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