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Long-term hydrologic recovery after wildfire and post-fire forest management in the interior Pacific Northwest

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Abstract

Elevated wildfire activity in many regions in recent decades has increased concerns about the short- and long-term effects on water quantity, quality, and aquatic ecosystem health. Often, loss of canopy interception and transpiration, along with changes in soil structural properties, leads to elevated total annual water yields, peak flows, and low flows. Post-fire land management treatments are often used to promote forest regeneration and mitigate effects to terrestrial and aquatic ecosystems. However, few studies have investigated the longer-term effects of either wildfire or post-fire land management on catchment hydrology. Our objectives were to quantify and compare the short- and longer-term effects of both wildfire and post-fire forest management treatments on annual discharge, peak flows, low flows, and evapotranspiration (AET). We analyzed ten years of pre-fire data, along with post-fire data from 1 to 7 and 35 to 41 years after wildfire burned three experimental catchments in the Entiat Experimental Forest (EEF) in the Pacific Northwest, USA. After the fire, two of the catchments were salvage logged, aerially seeded, and fertilized, while the third catchment remained as a burned reference. We observed increases in annual discharge (150–202%), peak flows (234–283%), and low flows (42–81%), along with decreases in AET (34–45%), across all three study catchments in the first seven year period after the EEF wildfire. Comparatively, annual discharge, peak flows, lows flows, and AET had returned to pre-fire levels 35–41 years after the EEF fire in the two salvage logged and seeded catchments. Surprisingly, in the catchment that was burned but not actively managed, the annual discharge and runoff ratios remained elevated, while AET remained lower, during the period 35–41 years after the EEF fire. We posit that differences in long-term hydrologic recovery across catchments were driven by delayed vegetation recovery in the unmanaged catchment. Our study demonstrates that post-fire land management decisions have the potential to produce meaningful differences in the long-term recovery of catchment-scale ecohydrologic processes and streamflow.

KEYWORDS
Discharge, evapotranspiration, low flows, peak flow, salvage logging, streamflow, vegetation recovery, wildfire

1 | INTRODUCTION

Wildfire is a global phenomenon with a long history of influencing both terrestrial and aquatic ecosystems (Agee, 1996; Bowman et al., 2009; Imeson, Verstraten, Van Mulligen, & Sevink, 1992; Prosser & Williams, 1998; Scott, 2000; Townsend & Douglas, 2000). In particular, extreme wildfire events – large spatial extent, high severity, and costly suppression – can have considerable environmental, economic, and social effects (Bowman et al., 2017). In recent decades, there has been increasing concern that climate change and aggressive fire suppression efforts have produced and will continue to produce, increased wildfire activity (e.g. fire season length, area burned, and fire severity) in many forested regions (Abatzoglou & Kolden, 2013; Flannigan et al., 2013; Schoennagel et al., 2017). In turn, this has resulted in considerable attention on the potential short-term and longer-term effects of forest fires on water quantity, water quality, aquatic ecosystem health, and downstream community water supply (Bladon, Emelko, Silins, & Stone, 2014; Emelko, Silins, Bladon, & Stone, 2011; Martin, 2016; Robinne et al., 2018).

Wildfires can affect water supply by influencing a range of hydrological processes in forested headwater catchments, where most discharge is generated (Brown, Hobbins, & Ramirez, 2008; Soulsby, Tetzlaff, & Hrachowitz, 2009). Removal of the forest canopy generally results in decreased interception and transpiration, leading to increased water available for runoff (Cardenas & Kanarek, 2014; Lavabre, Torres, & Cernesson, 1993; Nolan, Lane, Benyon, Bradstock, & Mitchell, 2014; Seibert, McDonnell, & Woodsmith, 2010; Soto & Diaz-Fierros, 1997; Zhou, Zhang, Vaze, Lane, & Xu, 2015). Moreover, wildfires can affect the physical properties of the soil surface in many ways that influence the hydrological response of burned catchments to precipitation events. For example, wildfires can increase soil-water repellency, soil sealing, surface crust formation, soil pore clogging, and bulk density due to collapse of soil aggregates (Balfour, Doerr, & Robichaud, 2014; Doerr, Shakesby, & Walsh, 2000; Larsen et al., 2009; Larson-Nash et al., 2018; Nyman, Sheridan, Smith, & Lane, 2014; Robichaud, Lewis, Wagenbrenner, Ashmun, & Brown, 2013). In turn, these effects on soil physical properties can influence soil hydraulic properties, such as hydraulic conductivity and sorptivity, which can reduce infiltration or shift runoff generation pathways (Ebel & Moody, 2017). These changes can increase the potential for elevated peak flows, low flows, and annual discharge (Bart, 2016; Helvey, 1980; Kinoshita, Hogue, & Napper, 2014; Lavabre et al., 1993; Scott, 1993; Wine & Cadol, 2016).

Due to increased wildfire activity, there has been substantial research in recent years on the effects of wildfire on discharge; however, the vast majority of studies have focussed on the initial (<5 years) post-fire effects (Hallema et al., 2017; Kinoshita & Hogue, 2015; Smith, Sheridan, Lane, & Bren, 2011). Comparatively fewer studies have investigated the longer-term legacy of wildfire effects on catchment hydrology (Hallema et al., 2018; Saxe, Hogue, & Hay, 2018). Certainly, the majority of studies have illustrated the greatest effects during the first several years, followed by a decline at various rates before returning to a near pre-fire condition (Ebel & Mirus, 2014; Vieira, Malvar, Fernandez, Serpa, & Keizer, 2016). However, observations of the rates of recovery have been highly variable, with hydrologic recovery noted to occur between 3 and 15 years (Cerdà & Doerr, 2005; Goetz, Fiske, & Bunn, 2006; Robichaud et al., 2013). In some cases, hydrologic recovery has not occurred by the end of the study (Bart, 2016; Wine & Cadol, 2016). The high degree of variability in the longevity and trajectory of the recovery curve is, in part, due to the complexity of many interacting factors, including fire severity, catchment physiography, vegetation composition and regrowth, soils, geology, climate, site disturbance history, and post-fire land management (Cerdà & Robichaud, 2009; Hessburg et al., 2016; Kinoshita & Hogue, 2011; Lopez Ortiz et al., 2019; Prats, Wagenbrenner, Martins, Malvar, & Keizer, 2016; Wittenberg & Inbar, 2009). Given the recent shifts in wildfire activity, there is a critical need to improve understanding of hydrologic recovery to facilitate improved models and predictions for post-fire land and water management decisions (Hallema, Robinne, & Bladon, 2018).

Additionally, it is increasingly important to improve our understanding of the efficacy of post-fire land management treatments, which are often used to promote forest regeneration, speed recovery, and mitigate effects to terrestrial and aquatic ecosystems (Leverkus et al., 2018; Robichaud, Beyers, & Neary, 2000). Common post-fire forest management approaches include salvage logging, emergency stabilization, subsoiling (cutting furrows along the contour of hillslopes), contour-felled logs, application of straw wattle to hillslopes, and seeding or replanting of hillslopes (Lindenmayer et al., 2004; Munson et al., 2015; Wagenbrenner, MacDonald, & Rough, 2006). While many of these post-fire management strategies are broadly used, there remains considerable debate about their efficacy due to a lack of supporting scientific evidence (Donato et al., 2006; Leverkus, Puerta-Pinero, Guzmán-Álvarez, Navarro, & Castro, 2012; McIver & Starr, 2001). In some cases, there has been evidence that post-fire forest management techniques can create additional site disturbance and enhance post-fire runoff, erosion, and sediment delivery to streams (Karr et al., 2004; Wagenbrenner, MacDonald, Coats, Robichaud, & Brown, 2015). However, we are unaware of any studies investigating the longer-term (>15 years) efficacy of post-fire forest management at mitigating the effects of wildfire on discharge.

In this study, the U.S. Department of Agriculture, Forest Service, Entiat Experimental Forest (EEF), which is located on the eastern slope of the Cascade Mountains in Washington State, USA, provided a rare and unique opportunity to investigate the effects of wildfire and post-fire forest management on discharge over multiple timescales (Helvey, 1980; Woodsmith, Vache, McDonnell, & Helvey, 2004). In the EEF, a paired watershed study began in 1961 with the objectives of quantifying the impacts of forest harvesting on discharge (Helvey, Fowler, Klock, & Tiedemann, 1976). After ten years of discharge data collection, the three EEF study catchments were severely and uniformly burned as part of a 486 km^2 wildfire complex in 1970 (Helvey, Tiedemann, & Fowler, 1976; Tiedemann & Klock, 1973). As such, the research objectives shifted to the effects of wildfire on discharge and post-fire forest management, as two of the catchments were salvage logged and aerially seeded and fertilized (Helvey, 1980; Seibert et al., 2010; Tiedemann & Klock, 1973). However, measurements were discontinued in 1977 after demonstrating that post-fire annual streamflow had at least doubled (discharge increased

~107–472 mm year^{-1}) with both low and high flows affected by the fire (Helvey, 1980). Between 2003 and 2004, gauging stations and meteorological stations were reestablished in the EEF, with the objective of exploiting "an opportunity to further analyze and build on an existing data set to increase understanding of the effects of severe wildfire on water quantity, quality, and timing, as well as increase understanding of long-term hydrologic recovery following severe disturbance such as fire" (Woodsmith et al., 2004).

Thus, our primary objective was to compare and contrast the short- (1–7 years post-fire) and longer-term (35–41 years post-fire) effects of wildfire on catchment hydrological processes, including evapotranspiration (AET), peak flows, low flows, annual discharge, and runoff ratios. Additionally, we sought to determine if post-fire land management, including salvage logging and seeding, affected the short- and longer-term recovery of catchment hydrological processes. Congruent with our expectation, we found that annual streamflow, peak flows, low flows, and runoff ratios were elevated immediately after the fire in all of the burned catchments. However, surprisingly we found evidence that streamflow and runoff ratios remained elevated 35–41 years after the fire in the catchment that received no post-fire land management, while the catchments that were salvage-logged and seeded had recovered hydrologically.

2 | METHODS

2.1 | Study sites

The EEF is located on the east slope of the Cascade Range in North Central Washington, USA at 47°56'N, 120°27'W (Figure 1). The EEF is in the Entiat River watershed, which drains into the Columbia River Basin. The study site includes three steep (mean slope ~50%), headwater catchments – Burns, McCrea, and Fox Creeks – each with a mean area of ~500 ha (Table 1) (Helvey, 1980). The catchments are snow-dominated, receiving 70% of their precipitation as snow, resulting in peak flows during snowmelt in May and June (Helvey, Fowler, et al., 1976). The catchments are underlain by bedrock that consists of primarily granodiorite and quartz diorite with some fluvioglacial deposits (Tabor et al., 1987). Soils are entisols composed of coarse sandy loams with interspersed layers of pumice and ash deposits from nearby Glacier Peak (Helvey, Fowler, et al., 1976; Tabor et al., 1987). Previous research in the EEF illustrated that the soils and subsurface geology were conducive to significant groundwater contributions to discharge (Alley, 2007).

Before the fire, the catchments were dominated by *Pinus ponderosa* (ponderosa pine) in the lower elevations, *Pseudotsuga menziesii* (Douglas-fir) and *Pinus contorta* (lodgepole pine) in the middle elevations, and *Pinus albicaulis* (whitebark pine) in the higher elevations (Table 2) (Helvey, Fowler, et al., 1976). After the wildfire, Burns and McCrea catchments were salvage logged (Helvey, 1980). Salvage logging operations were performed using caterpillar-type tractors and rubber-tired skidders (30% of area), high lead and ground skidding with cables (3% of area), and helicopters due to steep slopes (67% of area) (Helvey, 1980). Two roads were built along the elevation contours to facilitate wood removal from the catchments after salvage logging. After salvage logging, these two catchments were aerially seeded with a mixture of grasses, followed by aerial fertilizer application (Helvey, 1980). Vegetation surveys one year after aerial seeding confirmed that the majority of seeds had successfully germinated (Tiedemann & Klock, 1973). Between 1975 and 1977, ponderosa pine and Douglas-fir seedlings were planted in areas where natural reproduction was lacking

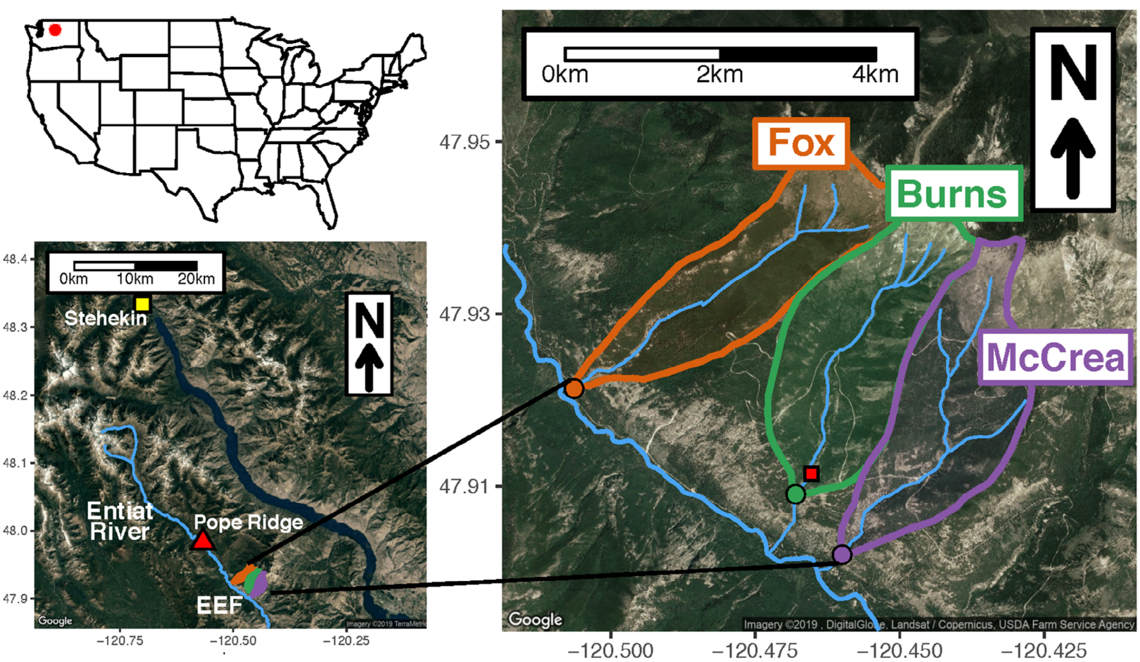

FIGURE 1 Map of Entiat Experimental Forest (EEF) with Burns, McCrea, and Fox Creeks and catchment boundaries and outlet (circles) and Burns meteorological station (red square) (right). Inset of Entiat region with Stehekin station and Pope Ridge station (lower left)

TABLE 1 Characteristics of the study catchments, Burns, McCrea, and Fox Creeks, from the Entiat Experimental Forest

Catchment	Area (km^2)	Elevation range (m)	Mean elevation (m)	Aspect azimuth (°)
Burns	5.54	842–2156	1403	205
McCrea	5.11	647–2150	1348	210
Fox	4.73	604–2166	1495	237

TABLE 2 Precipitation, discharge, air temperature, vegetation, and post-fire land management treatment for the pre-fire, immediate post-fire (post-short), and long-term post-fire (post-long) periods. Values presented are median and interquartile range in parentheses during the hydrologic year

		Time period		
Parameter	Catchment	Pre-fire: 1961–1970	Post-short†: 1971–1977	Post-long: 2005–2011
Precipitation (mm $year^{-1}$)	Burns	905 (824–950)	950 (801–1022)	984 (874–1015)
	McCrea	866 (784–910)	911 (762–983)	945 (835–976)
	Fox	932 (851–977)	977 (828–1049)	1,011 (901–1042)
Discharge (mm $year^{-1}$)	Burns	157 (145–181)	475 (271–650)	175 (160–233)
	McCrea	107 (104–125)	319 (220–431)	116 (103–143)
	Fox	157 (151–194)	393 (320–500)	237 (210–294)
Air temperature (°C)	All	7.2 (7.0–7.5)	7.7 (7.1–8.0)	7.1 (6.8–7.3)
Vegetation and treatment	All	• Ponderosa pine in lower elevation; • Douglas-fir and lodgepole pine in mid elevation; • Whitebark pine in high elevation	• McCrea/Burns: road construction, salvage logging, aerially seeding and fertilized; • Fox: no roads, logging, or seeding	• Ponderosa pine and Douglas-fir in lower and mid elevation;‡ • Lodgepole in mid and high elevation‡

†Burns Creek data included seven years of post-short data, Fox and McCrea Creeks only included four years of data due to flume destruction from debris flows.
‡Based on vegetation surveys from 2015 and 2016.

(Helvey, 1980). The Fox catchment remained unlogged with no roads and served as the reference (burned only) catchment.

In the early 2000s, small patches of tree die-off were observed in all three catchments (Elsner, Hamlet, Woodsmith, Littell, & Istanbulluoglu, 2011). Based on vegetation surveys in 2015 and 2016 there were slight shifts in the dominant vegetation types with elevation. Specifically, ponderosa pine and Douglas-fir dominated lower elevations, while lodgepole pine dominated middle and higher elevations (Table 2). Additionally, there was generally more ponderosa pine in Burns Creek compared to McCrea and Fox Creeks, which had more lodgepole pine (D. Peterson, unpublished data). The median basal area was 10.1 m^2 ha^{-1} in Burns Creek, 17.6 m^2 ha^{-1} in McCrea Creek, and 9.3 m^2 ha^{-1} in Fox Creek. Tree density was 636 trees ha^{-1} for Burns Creek, 1158 trees ha^{-1} for McCrea Creek, and 2317 trees ha^{-1} for Fox Creek. Additionally, the median tree diameter at breast height (DBH; 1.3 m above the ground) was 11 cm in Burns Creek, 10 cm in McCrea Creek, and 6 cm in Fox Creek.

2.2 | Data and statistical analyses

2.2.1 | Discharge

Hydrometeorological data, including discharge, precipitation, and other climatic related data, were collected for the following three time periods: ten years during the pre-fire period of 1961 to 1970 (pre-fire), during the seven year period after the wildfire from 1971 to 1977 (post-short), and for seven years in the long-term post-fire recovery period from 2005 to 2011 (post-long). During the pre-fire period, discharge was determined from continuous measurements of stage through sharp-crested, 120 V-notch concrete weirs, sealed to bedrock, at the outlet of each of the three study catchments (Helvey & Fowler, 1999).

In mid-March 1972 record high air temperatures induced rapid melting of an exceptionally deep snowpack producing sharply elevated flows across the EEF (Helvey, 1973). In the McCrea Creek catchment, these conditions triggered a localized (approximately 150 m^2, based on post-event photos) slope failure in weathered granitic material initiating a debris flow that destroyed the weir. Intense rainstorms in early June 1972 initiated a similar slope failure and debris flow in the Fox Creek catchment destroying that weir (Helvey, 1973). Similar debris flows also occurred in the Burns Creek catchment during this period, but the weir was not adversely affected (Helvey, 1980). In the summer and fall of 1972, the destroyed weirs in McCrea and Fox Creeks were replaced with Parshall flumes constructed tightly against the bedrock surface (Helvey, 1980; Helvey & Fowler, 1999). As a result, during the post-short period there were only four complete years of discharge data for McCrea and Fox Creeks. Three of those years occurred after the debris flow, which introduced substantial sediment to the weirs and created multiple data gaps in these two watersheds. Thus, gaps in the discharge data were filled using the complete discharge data record from Burns Creek (Helvey & Fowler, 1999).

2.2.2 | Precipitation

From 1961 to 1977, precipitation data were collected at the Burns Creek met station at 920 m with a shielded, weighing bucket with a 203 mm opening (Helvey & Fowler, 1999; Seibert et al., 2010). Further inspection of the data revealed four years where the precipitation record was uncharacteristically low. This was based on a comparison with precipitation from the National Weather Service station at Stehekin (48°20'N, 120°42'W, 351 m elevation), which is roughly 45 km from EEF (Figure 1). Using the entire period of record from these early years, the ratio of average annual precipitation at the Burns Creek meteorological station relative to the Stehekin gauge was 0.65. However, removing the four years with uncharacteristically low precipitation at Burns Creek met (ratio < 0.50), produced a ratio of 0.74. Thus, we filled these four years using the regression relationship (R^2 = 0.50) between the Burns Creek weir monthly precipitation and Stehekin monthly precipitation.

From 2005 to 2011, precipitation was measured with an unshielded tipping bucket rain gauge at the Burns Creek met station. Given that the tipping bucket rain gauges were not outfitted with overflow tubes to measure snowfall, we had to estimate precipitation during snowfall periods. To do this, we differentiated snowfall and rain events based on air temperature at the Burns Creek, using 2 °C as the threshold, after Kienzle (2008). During rain events we used the tipping bucket data for precipitation. During this same period, we developed a regression relationship (R^2 = 0.65) based on monthly precipitation at the Burns Creek met station and Pope Ridge SNOTEL site (47°59'N, 120°34'W, 1,094 m elevation), approximately 10 km from EEF (Figure 1). We then used this regression relationship to fill in Burns Creek precipitation during periods of snowfall.

After we established a continuous precipitation time series at Burns Creek for the three time periods, we used precipitation data from the storage gauges at 1400 and 2133 m in Burns Creek, which were collected approximately twice a year from 1970 to 1977, and the elevation distribution for each catchment to calculate average daily precipitation. Using the method from Daly, Neilson, and Phillips (1994) we calculated the slope of the relationship between precipitation and elevation to be 0.61 mm m^{-1} (R^2 = 0.90), which was within the range of observed values for the Western US (Daly et al., 1994). We then interpolated precipitation across each catchment for each 150 m elevation band as the product of the slope of the precipitation–elevation relationship and the difference in elevation between the observed measurements at the Burns Creek weir and each 100 m elevation band. We then calculated the total daily area-weighted precipitation for each catchment.

2.2.3 | Statistical analyses

We used daily discharge data to calculate annual low flows, peak flows, total annual discharge, and runoff ratios (total annual streamflow/total annual precipitation) during each water year for all three of the study catchments. We calculated weekly low flows and peak flows by summarizing daily flow during each calendar week. For each catchment and year, we also calculated the $Q50_{day}$ index, which corresponded to the date on which 50% of total annual discharge for the water year had passed the stream gauge. The $Q50_{day}$ index is analogous to the centre of mass date, which has been used as an index of timing of snowmelt runoff (McCabe & Clark, 2005). For each catchment for the three time periods, we also developed flow duration curves (FDCs) to facilitate comparisons of runoff generation between catchments and time periods (Yaeger et al., 2012). We estimated actual AET using a water balance method, which assumes no change in catchment storage, by subtracting the total annual discharge from the annual precipitation (AET = $P - Q$) for each catchment during each water year. We also calculated the evaporative index as the quotient of AET divided by annual precipitation to provide insights into catchment water partitioning (Creed et al., 2014). Given that runoff ratio, AET, and evaporative index are all derived from P and Q, statistical inferences from one metric may apply to another.

To quantify how wildfire at the EEF altered catchment hydrology over time (objective 1), we performed statistical analyses comparing discharge and AET metrics across the three time periods. Specifically, we used the nonparametric Kruskal–Wallis one-way analysis of variance (Kruskal & Wallis, 1952) followed by a post-hoc multiple comparison Dunn's test (Dunn, 1964) to compare low flows, peak flows, total annual discharge, runoff ratio, $Q50_{day}$, AET, and evaporative index for each of the three catchments between the time periods.

To quantify the impact of post-fire land management on AET and discharge (objective 2), we calculated the change in AET and streamflow metrics from individual years to the pre-fire medians. For example, for annual discharge in Burns Creek during the post-short period we calculated the change, as follows:

$$\Delta Q_{i,\text{post-short,Burns}} = Q_{i,\text{ post-short,Burns}} - \text{median}\left(Q_{\text{pre-fire,Burns}}\right) \quad (1)$$

where i is the year from the post-short period, $Q_{i,\text{post-short,Burns}}$ the year i annual discharge, and $Q_{\text{pre-fire,Burns}}$ the discharge from the entire pre-fire period.

We then used the Kruskal–Wallis test to compare the different AET and streamflow metrics between the burned, reference catchment (Fox Creek) and the two burned and salvage logged catchments (Burns and McCrea Creeks). Since this analysis was only performed as single comparisons (i.e. reference *vs* salvage logged), a post-hoc multiple comparison Dunn's test was not required. We implemented the Kruskal–Wallis tests for each of the seven AET and streamflow metrics for both the post-short and post-long periods.

We followed these Kruskal–Wallis and Dunn's tests with the Benjamini–Hochberg procedure to control the false discovery rate of the multiple comparisons tests (Benjamini & Hochberg, 1995). We chose a false discovery rate of 0.1 to calculate the Benjamini–Hochberg critical values. With 63 Dunn's tests comparisons across time periods (three time period comparisons, three catchments, and seven metrics) and 14 Kruskal–Wallis tests comparisons across post-fire management (two time period comparisons and seven metrics) there were 77 total *p*-values. We then calculated the Benjamini–Hochberg critical value with the 77 raw *p*-values, and this critical value was used to determine if individual comparisons were significant based on raw *p*-values below the critical value. In this case, the critical value was calculated as 0.044. Results from the Kruskal–Wallis and Dunn's tests are summarized in the Tables S1–S5.

We also analyzed the FDCs to provide additional evidence of the effects of wildfire on catchment hydrology over time (objective 1) and to assess the effects of post-fire land management, including salvage logging and seeding, on the short- and longer-term recovery of catchment hydrological processes (objective 2). Specifically, we tested our null hypothesis of no change in FDCs among the three time periods with the non-parametric two-sample Kolmogorov–Smirnov (KS) test (Smirnov, 1948). The KS test is considered an effective method for testing differences in streamflow due to flow alteration (Kroll, Croteau, & Vogel, 2015; Vogel & Fennessey, 1994). Our alternative hypotheses for the FDCs were: (a) post-short > pre-fire (i.e. the discharge during the initial seven year period after fire was greater than discharge during the pre-fire period), (b) post-long > pre-fire (i.e. discharge 35–41 years after the fire remained elevated compared to the pre-fire period), and (c) post-short > post-long (i.e. discharge during the initial seven year period after the fire was greater than 35–41 years after the fire due to hydrologic recovery).

We tested our hypotheses with two approaches. In the first approach, which was similar to that reported in Gao, Vogel, Kroll, Poff, and Olden (2009), we performed nine individual KS tests comparing median annual FDCs for the three time periods within each of the three catchments. Second, we compared the FDCs for each catchment from the three time periods with jackknife resampling after the approach of Kroll et al. (2015). This method reduced the chance of an exceptionally wet or dry year causing a type I error. To employ this method, we first calculated the median pre-fire FDC for each catchment. We then developed a series of FDCs for each catchment and each time period using an exhaustive jackknife resampling in five-year increments. Because Burns Creek had ten complete years of pre-fire data, this resulted in 252 five-year FDCs. However, McCrea and Fox Creeks only had nine complete years of pre-fire data, resulting in 126 five-year FDCs. For the post-short period, we were only able to analyze data from Burns Creek since both McCrea and Fox Creeks only had four complete years of discharge data. For all three catchments, we had seven years of discharge data during the post-long period, which resulted in 21 five-year FDCs via jackknife resampling. We calculated the KS test statistic as the maximum distance between the pre-fire median annual FDC and each of the sampled FDCs from the five-year jackknife combinations for each of the three time periods.

To test our hypotheses about changes in FDCs between the three time periods, we calculated a critical value from the pre-fire FDC KS test. We did this by calculating the Weibull plotting position for all pre-fire KS statistics from an individual catchment and then ranked those values. The critical value was determined by interpolating the KS test statistic with an exceedance probability of 0.05 based on the ranked Weibull plotting position. To test our hypotheses, we then compared the pre-fire FDC KS statistic critical value for each catchment to the post-short and post-long FDC KS statistics. We rejected the null hypothesis if the KS test statistic for all years within a post-fire test (i.e. pre-fire median FDC *vs* post-short FDC and pre-fire median FDC *vs* post-long FDC) were greater than the critical value from the pre-fire test (i.e. pre-fire median FDC *vs* pre-fire FDC).

We performed all analyses in R version 3.5.1 (R Core Team, 2018). We interpreted *p*-values from all statistical analyses based on their strength of evidence against the null hypothesis, as suggested by Arsham (1988) and Sterne and Smith (2001).

3 | RESULTS

3.1 | Short- and long-term effects of wildfire on catchment hydrology

3.1.1 | Annual discharge

Median annual discharge increased from the pre-fire period (1961–1970) to the post-short period (1971–1977) by ~202% in Burns Creek, ~199% in McCrea Creek, and ~150% in Fox Creek (Table 2, Figure 2). This increase equated to a median increase of 317 mm year^{-1} in Burns Creek, 212 mm year^{-1} in McCrea Creek, and 236 mm year^{-1} in Fox Creek (Table 2, Figure 2). Statistically, there was strong evidence ($p < .01$) that median annual discharge was greater in all three catchments during the initial seven year period after the fire (post-short) compared to the pre-fire period (Table S3). Moreover, the FDCs appeared to uniformly shift upwards across the entire flow regime from the pre-fire to the post-short period (Figure 3). Statistically, there was very strong evidence (KS tests, $p < .0001$) that the median annual FDCs were elevated during the post-short period compared to the pre-fire period for all three catchments (Table 3). Jackknife resampling analysis of the FDCs in Burns Creek further confirmed these conclusions as the minimum post-short KS statistic was ~262% greater than the maximum pre-fire KS statistic (Figure 4). Finally, there was strong evidence (Table S3, $p < .01$) that runoff ratios were also elevated in all three catchments in the post-short period compared to the pre-fire period (Figure 5).

Analysis of the long-term data (2005–2011; 35–41 years after wildfire), indicated that annual discharge in all three catchments substantially declined relative to the first seven year period after the fire (post-short). Specifically, the median annual discharge during the post-short period was greater than the post-long period by ~171% in Burns Creek, ~175% in McCrea Creek, and ~67% in Fox Creek (Table 2, Figure 2). Statistically, there was moderate evidence ($p < .05$) that both annual discharge and runoff ratio were greater in the post-short period compared to the post-long period in both Burns and McCrea

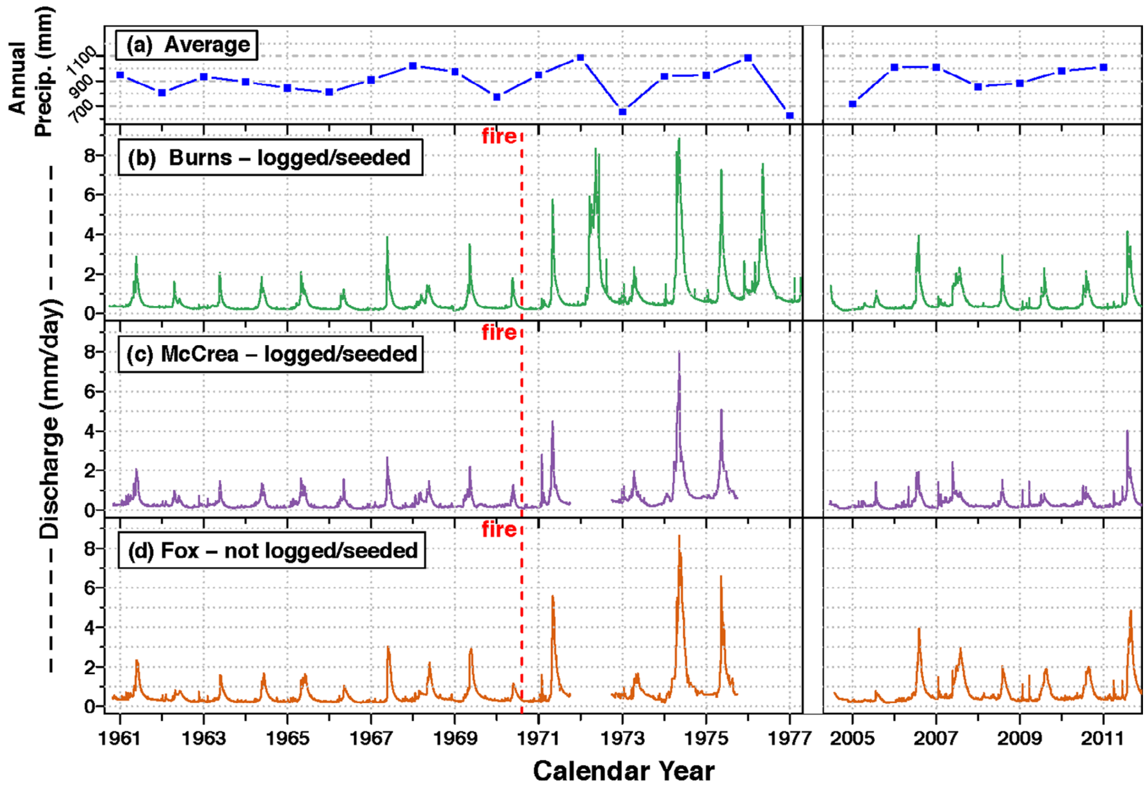

FIGURE 2 (a) Annual average precipitation across all three catchments and daily discharge at (b) Burns, (c) McCrea, and (d) Fox Creeks. Red-dotted line indicates when the wildfire occurred

Creeks (Table S3). Comparatively, in Fox Creek, there was only suggestive evidence that annual discharge and runoff ratios were greater during the post-short period compared to the post-long period (p = .06). The FDCs provided visual evidence that streamflow was almost uniformly higher across the entire flow regime during the post-long period compared to the pre-fire period (Figure 3). As such, there was strong statistical evidence (p < .001) that the annual FDCs were lower 35–41 years after the fire compared to the first seven year period after the fire (Table 3).

The majority of metrics we used to quantify and analyze annual discharge remained slightly greater in all three catchments during the post-long period relative to the pre-fire period. Specifically, median annual discharge in the post-long period was ~11% greater in Burns Creek, ~8% greater in McCrea Creek, and ~51% greater in Fox Creek compared to the pre-fire period (Table 2, Figure 2). Likewise, the median runoff ratio was ~8% greater in Burns Creek, ~3% lower in McCrea, and ~22% greater in Fox Creek (Figure 4). However, statistically there was no evidence for differences in annual discharge between the pre-fire and post-long periods in either Burns (p = .19) or McCrea (p = .35) Creek. Interestingly, there was suggestive evidence (p = .08) that annual discharge remained elevated in Fox Creek 35–41 years after the fire compared to the pre-fire period (Table S3). Similarly, there was also moderate evidence (p = .05) that the runoff ratios remained elevated in Fox Creek during the post-long period compared to the pre-fire period, but no evidence of elevated runoff ratios in either Burns or McCrea Creeks (Figure 5). For comparison, the FDCs appeared to be slightly elevated across the entire flow regime for the post-long period relative to the pre-fire period in all three catchments (Figure 4). Statistically, there was very strong evidence (p < .001) that the FDCs from all three catchments remained elevated in the post-long period compared to the pre-fire period (Table 3). For the post-long FDC jackknife resampled KS statistics, all KS statistics for all catchments except for the single lowest KS statistic in Burns Creek were above the critical value determined from the pre-fire data (Figure 4).

3.1.2 | Peak flows, low flows, and timing

Unit area peak flows (maximum weekly discharge) were elevated in the first seven year period after the fire (post-short period), but returned to pre-fire levels 35–41 years after the fire (post-long period). These peak flows were driven by spring snowmelt, with a median peak flow date across all periods and catchments of May 17. The latest peak flow date of all years in the study was June 9, 2010, while the earliest was April 9, 1977, which was the driest year of the study (Figure 2). During the pre-fire period, median weekly unit area peak flows were ~12.1 mm week^{-1} (IQR: 9.9–16.2 mm week^{-1}) in Burns Creek, ~8.8 mm week^{-1} (IQR: 7.9–11.8 mm week^{-1}) in McCrea Creek, and ~11.1 mm week^{-1} (8.6–15.2 mm week^{-1}) in Fox Creek. In the post-short period, median weekly unit area peak flows were elevated ~234–283% to ~46.2 mm week^{-1} (IQR: 24.6–47.7 mm week^{-1})

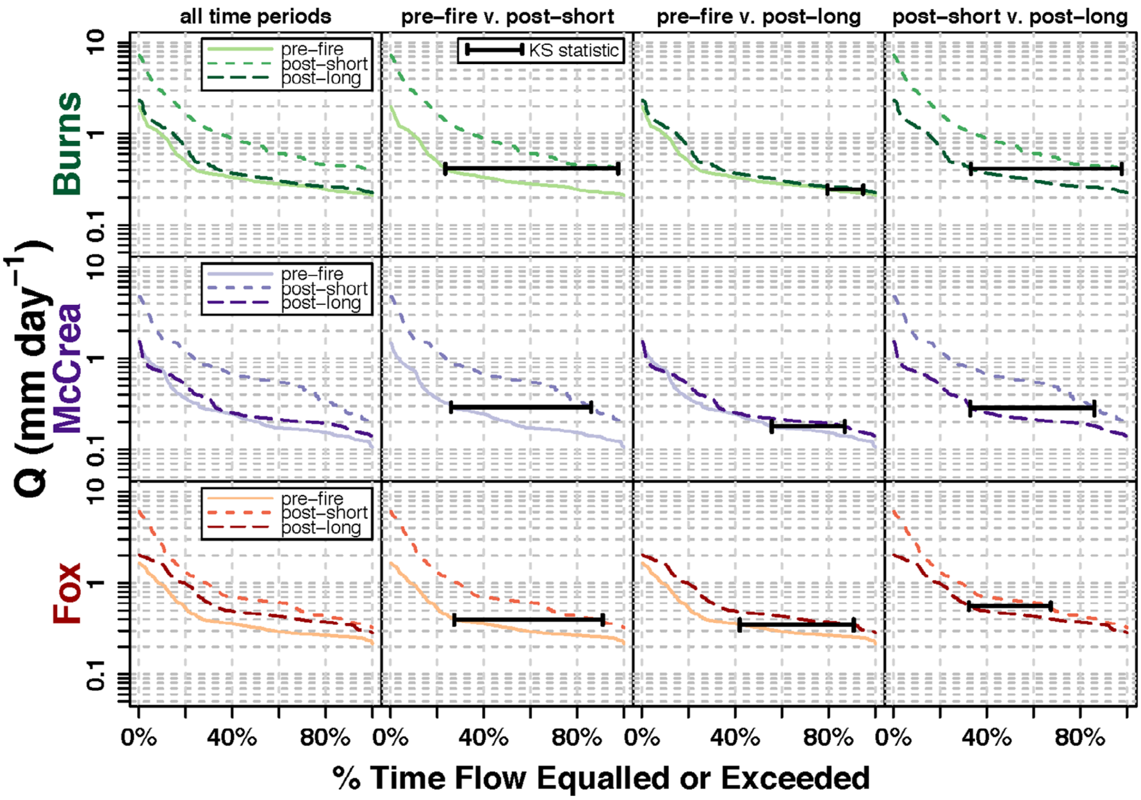

FIGURE 3 Median annual flow duration curves for Burns, McCrea, and Fox Creeks during pre-fire (1961–1970), post-short (1971–1977), and post-long (2005–2011) time periods. Black solid horizontal lines with brackets are Kolmogorov–Smirnov (KS) test statistics for each catchment pair and time period. The range of the horizontal KS lines corresponds to the lower and upper FDC exceedance probabilities in parentheses found in Table 3. The *y*-axis value for the KS lines corresponds to the discharge (*Q*) for each test found in Table 3

TABLE 3 Summary of Kolmogorov–Smirnov (KS) statistics for comparing discharge flow duration curves (FDC) across Burns, McCrea and Fox Creeks for pre-fire (1961–1970), post-short (1971–1977), and post-long (2005–2011) time periods. The symbol (> or <) indicates the alternate hypothesis of the KS test. The exceedance probabilities of the lower and upper FDC for each test are given in parentheses

	Pre-fire < post-short		Pre-fire < post-long		Post-short > post-long	
Creek – post-fire treatment	KS statistic	Q (mm day^{-1})	KS statistic	Q (mm day^{-1})	KS statistic	Q (mm day^{-1})
Burns – logged/seeded	**0.74** (0.24–0.98)	0.42	**0.15** (0.79–0.95)	0.25	**0.65** (0.33–0.98)	0.41
McCrea – logged/seeded	**0.60** (0.26–0.86)	0.29	**0.31** (0.56–0.87)	0.18	**0.53** (0.33–0.86)	0.29
Fox – not logged/seeded	**0.64** (0.27–0.91)	0.40	**0.49** (0.42–0.91)	0.35	**0.35** (0.32–0.67)	0.56

Note: The Burns, Pre-fire < Post-long (row 1, column 4) KS statistic is $p < 0.001$, all the remaining KS statistic values are $p < 0.0001$.

in Burns Creek, ~29.6 mm week^{-1} (IQR: 22.3–36.3 mm week^{-1}) in McCrea Creek, and ~38.9 mm week^{-1} (IQR: 29.8–43.5 mm week^{-1}) in Fox Creek. Statistically, there was strong evidence ($p < .01$) of elevated peak flows in the post-short period compared to the pre-fire period in Burns and McCrea Creeks, but moderate evidence of elevated peak flows in Fox Creek ($p = .05$) (Table S3).

During the post-long period, median weekly unit area peak flows were ~13.8 mm week^{-1} (IQR: 13.4–18.3 mm week^{-1}) in Burns Creek, ~7.8 mm week^{-1} (IQR: 6.9–11.0 mm week^{-1}) in McCrea Creek, and ~13.7 mm week^{-1} (IQR: 13.2–22.7 mm week^{-1}) in Fox Creek. Statistically, there was strong evidence weekly unit area peak flows were elevated in McCrea Creek during the first seven year period after the fire (post-short) compared to 35–41 years after the fire (post-long) ($p < .01$). However, there was only suggestive evidence in Burns Creek ($p = .07$) and no evidence in Fox Creek for differences in peak flows between the post-short and post-long periods. Finally, the weekly unit area peak flows remained elevated by ~15% in Burns Creek and ~24% in Fox Creek, but reduced by ~12% in McCrea Creek during the post-long period compared to the pre-fire period. However, there was no statistical evidence for differences in peak flows in any of the catchments between the pre-fire and post-long periods (Table S3).

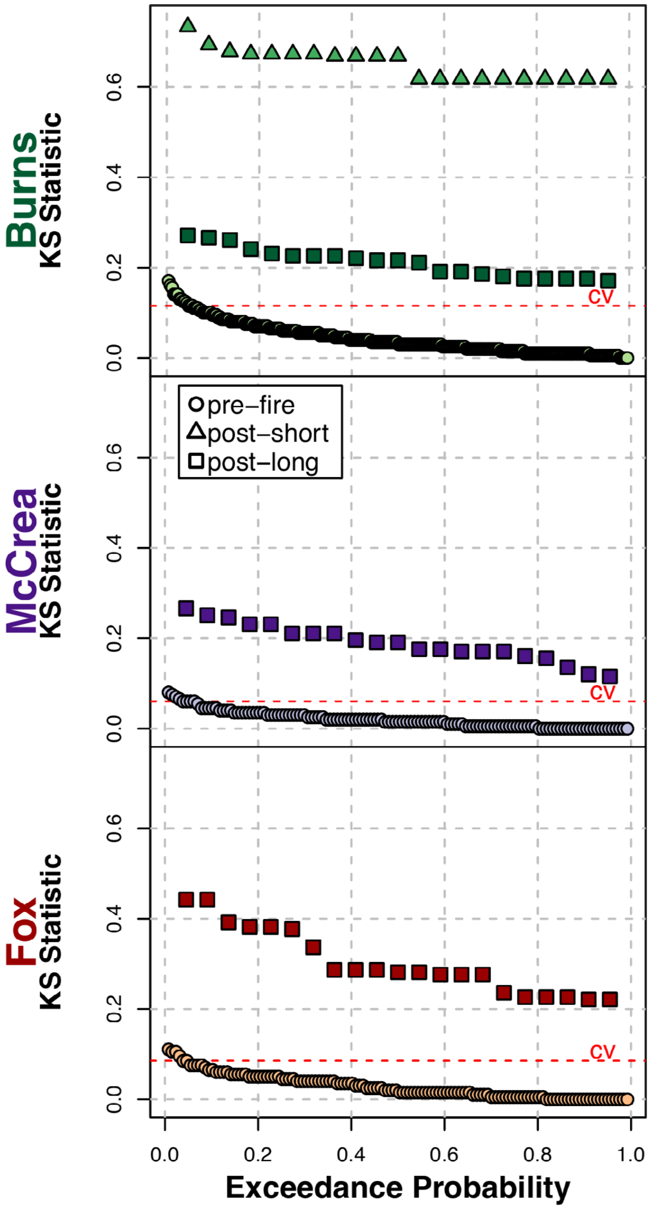

FIGURE 4 Kolmogorov–Smirnov (KS) test statistic *versus* exceedance probability between pre-fire (1961–1970) median flow duration curves (FDC) and post-short (1971–1977) and post-long (2005–2011) jackknifed FDCs across Burns, McCrea, and Fox Creeks. The critical value (cv), indicated by the red-dashed line, was based on the pre-fire 0.05 Weibull plotting position. McCrea and Fox Creeks post-short were not included due to insufficient years for jackknife resampling

Low flows (minimum unit area weekly discharge) were also greater during the post-short period compared to the pre-fire period. Specifically, during the pre-fire period, weekly unit area low flows were ~1.5 mm week^{-1} (IQR: 1.3–1.7 mm week^{-1}) in Burns Creek, ~0.9 mm week^{-1} (IQR: 0.71–0.96 mm week^{-1}) in McCrea Creek, and ~1.7 mm week^{-1} (IQR: 1.61–1.90 mm week^{-1}) in Fox Creek. In the post-short period, weekly unit area low flows were elevated ~42–81% to ~2.7 mm week^{-1} (IQR: 2.2–3.6 mm week^{-1}) in Burns Creek, ~1.4 mm week^{-1} (IQR: 1.3–2.3 mm week^{-1}) in McCrea Creek, and ~2.4 mm week^{-1} (IQR: 1.9–3.0 mm week^{-1}) in Fox Creek.

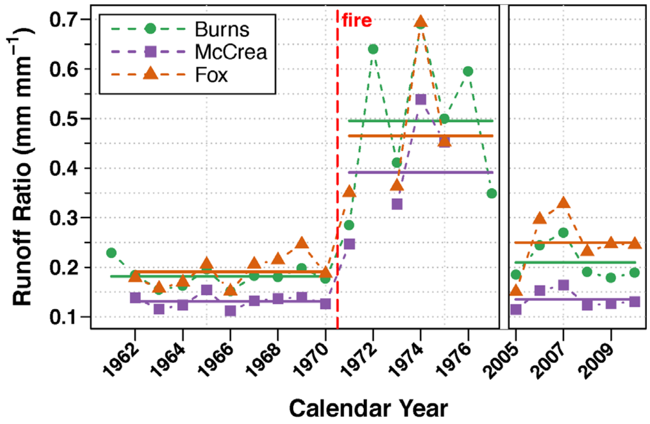

FIGURE 5 Runoff ratios across Burns, McCrea, and Fox Creeks and all three time periods. Solid lines are median runoff ratios for each catchment over pre-fire (1961–1970), post-short (1971–1977), and post-long (2005–2011) time periods

Statistically, there was strong evidence ($p < .01$) that low flows were elevated during the post-short period compared to the pre-fire period in both Burns and McCrea Creeks; however, in Fox Creek there was only suggestive evidence that low flows were different between the post-short and pre-fire period (Table S3). Comparatively, median low flows during the post-long period (35–41 years after the fire) were ~1.6 mm week^{-1} (IQR: 1.4–1.8 mm week^{-1}) in Burns Creek, ~1.0 mm week^{-1} (IQR: 0.8–1.1 mm week^{-1}) in McCrea Creek, and ~2.1 mm week^{-1} (IQR: 1.8–2.5 mm week^{-1}) in Fox Creek. Statistically, there was no evidence for differences in weekly unit area low flows between the post-long period and pre-fire period. However, there was strong to moderate evidence (Dunn's test, $p < .05$) that weekly unit area low flows were greater within the first seven year period after the fire (post-short) compared to 35–41 years after the fire (post-long) in two of the catchments (McCrea and Burns Creeks), but not in Fox Creek (Table S3).

Counter to our hypothesis, there was no evidence for differences in streamflow timing ($Q50_{day}$) between any of the three periods of study. The lowest raw p-value for all nine tests for differences in the $Q50_{day}$ was $p = .18$ for the Burns Creek pre-fire and post-short comparison (Table S3). The z-statistics were all positive for the pre-fire and post-long comparison, and all positive (negative) for the pre-fire and post-short (post-short and post-long), indicating flow timing was earlier in the pre-short period.

3.1.3 | Evapotranspiration

Annual rates of AET were lower in the first seven year period after fire (post-short) compared to the pre-fire period. The median pre-fire annual AET was 741 mm (IQR: 685–777 mm) in Burns Creek, 751 mm (IQR: 684–797 mm) in McCrea Creek, and 747 mm (IQR: 696–767 mm) in Fox Creek (Figure 6). During the post-short period, the annual AET declined to 411 mm (IQR: 391–468 mm) in Burns Creek, 458 mm (IQR: 417–546 mm) in McCrea Creek, and 486 mm

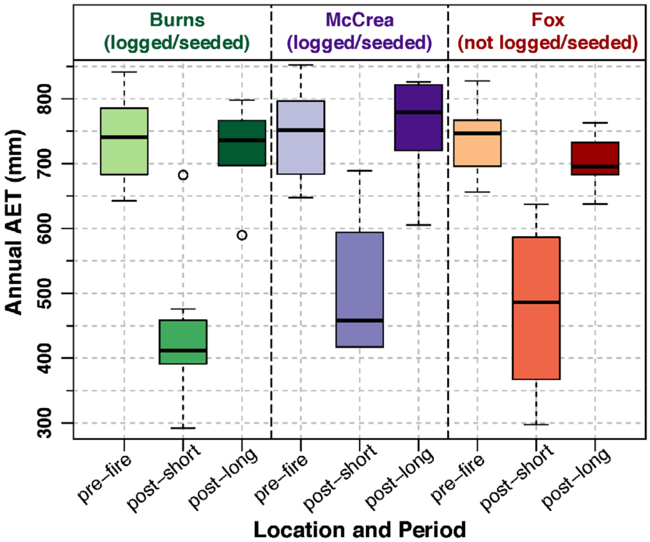

FIGURE 6 Boxplots of annual actual evapotranspiration (AET) for Burns, McCrea, and Fox Creeks for pre-fire (1961–1970), post-short (1971–1977), and post-long (2005–2011) time periods

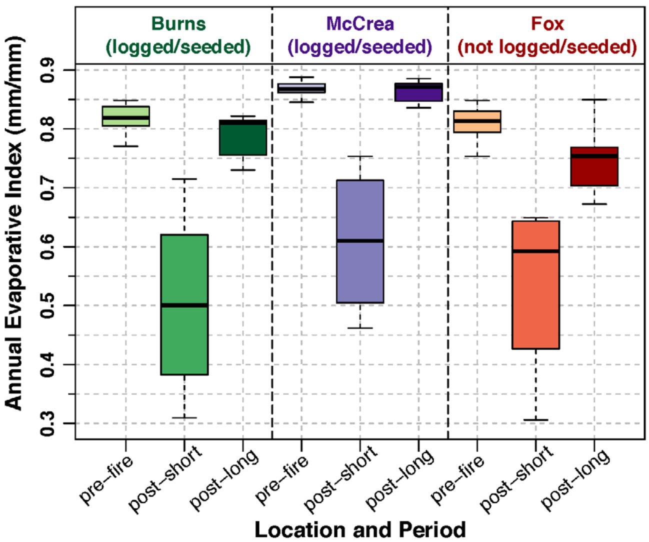

FIGURE 7 Boxplots of annual evaporative index for Burns, McCrea, and Fox Creeks for pre-fire (1961–1970), post-short (1971–1977), and post-long (2005–2011) time periods

(IQR: 401–560 mm) in Fox Creek. Statistically, there was moderate to strong evidence ($p < .05$) that annual AET was greater during the pre-fire period than the post-short period in all three catchments (Figure 6, Table S4). Similarly, there was also strong evidence that the evaporative index was greater in the pre-fire period compared to the post-short period across all three catchments (Figure 7). The evaporative index dropped by 39% in Burns Creek, 30% in McCrea Creek, and 20% Fox Creek during the first seven year period after the fire.

During the post-long period (35–41 years after the fire) the median annual AET was 735 mm (IQR: 705–760 mm) in Burns Creek, 779 (IQR: 725–820 mm) in McCrea Creek, and 695 (IQR: 684–725 mm) in Fox Creek. Statistically, there was strong evidence ($p < .01$) in Burns Creek and moderate ($p < .05$) evidence in McCrea Creek that both AET and the evaporative index were greater during the post-long period compared to the post-short period (Table S4). However, in Fox Creek there was only suggestive evidence that AET or evaporative index were different between the post-long and post-short periods.

The median AET in Fox Creek remained 51.3 mm lower during the post-long period compared to the pre-fire period (Figure 6). Comparatively, the median AET was only 4.7 mm lower in Burns Creek and was 27.5 mm greater in McCrea Creek during the post-long period compared to the pre-fire period (Figure 6). Statistically, except for evaporative index in Fox Creek, there was no evidence for differences in AET or the evaporative index between the pre-fire and post-long periods across all three catchments. There was only suggestive evidence ($p = .07$) that the evaporative index in Fox Creek remained lower during the post-long period compared to the pre-fire period.

3.2 | Effects of post-fire land management on catchment hydrology

Our analysis of changes in discharge metrics across the three time periods of the study (pre-fire, post-short, and post-long) also provided evidence of the influence of post-fire land management on hydrologic recovery across the three study catchments. In the first seven year period after the fire, all three catchments appeared to respond similarly to the dominant effects of the wildfire. In direct comparisons between the burned and unmanaged catchment (Fox Creek) and the two post-fire salvage logged and seeded catchments (Burns and McCrea Creeks) there was no evidence that any of the discharge metrics (annual discharge, runoff ratio, maximum weekly discharge, minimum weekly discharge, and $Q50_{day}$) were different across the catchment groups during the for post-short period (Table S5). Comparatively, during the post-long period (35–41 years after the fire) there was moderate and suggestive evidence that runoff ratio and annual discharge, respectively, were greater in the burned only catchment (Fox Creek) compared to the post-fire salvage logged catchments (Table S5). Similarly, there was also suggestive evidence that annual AET and the evaporative index were lower in Fox Creek compared to the post-fire salvage logged catchments. Considering the suggestive evidence (presented earlier in Section 3) that annual discharge and the runoff ratios in Fox Creek remained greater during the post-long period compared to the pre-fire period, overall this is indicative that streamflow remained slightly elevated 35–41 years after the fire in this unmanaged catchment. Alternatively, the collective evidence suggests that the two catchments that were actively managed after the fire (salvage logged and seeded) had fully recovered during the long-term period of the study.

4 | DISCUSSION

Multiple lines of evidence from our study indicated that active post-fire land management in two catchments after the 1970 wildfire at the EEF may have increased the rate of long-term hydrologic recovery relative to an unmanaged catchment. In the two catchments that were salvage logged, aerially seeded, and fertilized (Burns and McCrea Creeks), the annual discharge, runoff ratios, AET, and evaporative index had almost all returned to pre-fire levels 35–41 years after the EEF fire. However, in the catchment that burned but was not actively managed (Fox Creek), the annual discharge and runoff ratios remained elevated, while AET and evaporative index remained lower, during the period 35–41 years after the EEF fire. Indeed, hydrologic recovery has been shown to vary depending on fire severity, aspect, vegetation, soil type, and post-fire weather (Feikema, Sherwin, & Lane, 2013; Kinoshita & Hogue, 2011; Pierson, Robichaud, & Spaeth, 2001). At the EEF, fire severity, aspect, and soils were generally uniform across catchments. Moreover, we found no evidence for differences in precipitation across periods, which suggests land cover change was a dominant driving factor for differences in discharge. In this case, we posit that harvesting of the standing dead wood, aerial seeding, and limited conifer planting of Burns and McCrea Creeks may have facilitated more productive long-term vegetation growth, leading to higher rates of AET and a more rapid return to pre-fire levels. Indeed, the median basal areas were ~1.1–1.9-times greater and the tree diameters were ~1.7–-1.8-times greater in the actively managed catchments compared to the unmanaged catchment.

Our results are consistent with other studies showing more rapid forest regeneration following post-fire land management (Donovan, Roberts, Wonkka, Wedin, & Twidwell, 2019; Ouzts, Kolb, Huffman, & Meador, 2015), which would also influence long-term hydrologic recovery. For example, Lopez Ortiz et al. (2019) found that active post-fire management increased ponderosa pine regeneration in northwestern California and southwestern Oregon. However, they also found that active post-fire management had no effect on Douglas-fir regeneration and, overall conifer regeneration was most heavily influenced by catchment aspect (Lopez Ortiz et al., 2019; Ohmann & Spies, 1998). In particular, they found reduced conifer regeneration on south aspects, which was attributed to higher drought stress and soil surface temperatures (Lopez Ortiz et al., 2019; Rosenberg, Blad, & Verma, 1983). Given that our study catchments at the EEF were also south facing, we speculate that this may have contributed to the delayed regeneration and hydrologic recovery in the unmanaged catchment. As such, we caution about broader interpretation of our findings because there remains a lack of consensus on whether post-fire management assists or hinders regeneration (Donato et al., 2006; Lindenmayer et al., 2004). Moreover, our findings must also be reconciled with the fact that there may be other negative consequences from post-fire forest management that must be considered, including loss of habitat, decreased species richness, increased sediment and turbidity in streams, and elevated short-term fire risk (Donovan et al., 2019; Lewis, Rhodes, & Bradley, 2019; McIver & Starr, 2001; Thorn et al., 2018). As a result, future research should attempt to provide more complete knowledge regarding the tradeoffs associated with post-fire management to facilitate effective forest and water management.

The apparent legacy effects (35–41 years after the EEF fire) on annual water yields in the unmanaged catchment (Fox Creek) were unexpected, but clearly demonstrate the value of long-term research (Laudon et al., 2017; Tetzlaff, Carey, McNamara, Laudon, & Soulsby, 2017). While a few post-fire studies have illustrated hydrologic recovery within 10 years of the fire (Brown, 1972; Wine & Cadol, 2016), the vast majority of studies have not continued long enough to observe hydrologic recovery (Kinoshita & Hogue, 2011; Kinoshita & Hogue, 2015; Robichaud et al., 2013; Saxe et al., 2018). Indeed, most studies have shown a peak in hydrologic impacts during the first several years (i.e. initial response), followed by a decline at varying rates (Ebel & Mirus, 2014; Noske, Nyman, Lane, & Sheridan, 2016; Vieira et al., 2016). However, the longevity and trajectory of the recovery curve is uncertain as it may be influenced by a broad range of factors, including fire severity, disturbance history, post-fire land management, catchment physiography, vegetation composition and regrowth, soils, geology, climate, and weather patterns in the early post-fire years (Emelko et al., 2016; Wine, Cadol, & Makhnin, 2018; Wittenberg & Inbar, 2009).

As such, we postulate that the long-term effects of the Entiat wildfire on annual water yields in the unmanaged catchment (Fox Creek) may have been related to the strong initial effects. As expected, we observed increases in annual discharge in all three of our study catchments during the first seven year period after the Entiat wildfire. However, the median increases in annual water yields were 150–202% (212–317 mm year^{-1}) during the early post-fire years, which was within the upper range of other moderate to high severity wildfires. For example, annual streamflow increased 134% (82–200%) in 12 burned watersheds in central and southern California during the first post-fire year (Bart, 2016). Similarly, mean annual water yields increased 19–101% during the first five years after wildfire burned two catchments in the Canadian Rocky Mountains (Mahat, Silins, & Anderson, 2016). Comparatively, the majority of published research has illustrated increases in annual water yields of 16–30% during the first several years after fire (Driscoll, Carter, & Ohlen, 2004; Hallema, Sun, et al., 2018; Lavabre et al., 1993; Scott, 1993; Wine & Cadol, 2016). Despite many observations of increased annual water yields after wildfire, there have also been several recent studies that have not observed evidence of wildfire effects on catchment hydrology, confirming the need for future research to improve our understanding of the factors influencing the variability in post-fire hydrological responses (Bart & Hope, 2010; Heath, Chafer, Van Ogtrop, & Bishop, 2014; Townsend & Douglas, 2000).

We also observed elevated peak flows (~234–283% increase) and low flows (~42–81% increase) across all three catchments during the first seven year period after the fire. However, there was no evidence that post-fire management affected these short-term responses. Moreover, there was no evidence that peak flows or low flows remained elevated in any of the catchments 35–41 years after the fire. Our observations of increased post-fire peak flows were expected, as previous analyses in the western US have shown that peak flows typically increase in the first two years following a wildfire and decrease over time (Hallema et al., 2017; Saxe et al., 2018). Specifically, peak discharges during the first one to two years after high-severity fires can increase by one to two orders of magnitude over values expected in unburned conditions, which have been attributed to a combination of factors, including decreased interception and infiltration, increased water repellency, and changes in soil hydraulic properties (Hallema et al., 2017; Kunze & Stednick, 2006). Similarly, the post-fire increases in low flows at EEF were not surprising – several studies in the western US have also observed 188–1090% increases in low flows in the first several years after wildfire, which have primarily been attributed to reduced transpiration (Kinoshita & Hogue, 2015; Saxe et al., 2018).

In our study, we observed a decrease in AET rates of ~35–45% across all three study catchments during the first seven year period after the EEF fire. However, there was no evidence of the effects of the fire on AET rates 35–41 years after the fire. Similar to our study, in the first three years after the Black Saturday fire in Australia, Nolan et al. (2014) observed 41% lower AET rates in a severely burned eucalyptus forest compared to an unburned catchment. The few other studies that have quantified wildfire effects on annual AET have illustrated a similar range of effects. For example, following the 2011 Las Conchas Fire in New Mexico, USA, Poon and Kinoshita (2018) estimated a 20–36% decrease in AET in catchments that had burned at high severity. Likewise, Roche, Goulden, and Bales (2018) also estimated substantial (~44–65%) and long-lasting (>14 years) declines in AET due to high severity wildfire in the Sierra Nevada range in California, US. Five years of eddy covariance measurements in a ponderosa pine dominated forest in northern Arizona showed a 12–30% decline an annual AET due to severe wildfire (Dore et al., 2010; Dore et al., 2012). Despite these recent studies, there is still much uncertainty about the magnitude and longevity of effects of forest disturbances on AET, which can have dramatic effects on water availability and, as such, should be increasingly quantified in future studies (Hallema, Robinne, & Bladon, 2018; Martin, 2016).

Finally, in contrast to our hypothesis, our analysis found no evidence that the EEF fire affected flow timing, as quantified with the $Q50_{day}$, which corresponds to the date on which 50% of total annual discharge for the water year passed the stream gauge. In comparison, Seibert et al. (2010) previously used the EEF data to develop a conceptual runoff model, which indicated that snowmelt would begin approximately one month earlier in the burned catchments due to a lower threshold temperature for snowmelt initiation. Interestingly, despite the likelihood of advanced timing of snowmelt, this did not appear to affect the timing of the annual flow volume. Indeed, removal of the forest canopy due to disturbance generally increases snow accumulation and loss through decreased interception and elevated ablation rates due to declines in snow albedo and more solar radiation at the snow surface (Broxton et al., 2015; Gleason, Nolin, & Roth, 2013; Harpold et al., 2014). Specifically, snow accumulation and melt timing may occur 9–24 days earlier in burned forests, resulting in earlier initiation of peak flows (Burles & Boon, 2011; Mahat et al., 2016; Wagner et al., 2014). However, the in-stream hydrologic response remains uncertain and is likely to be highly variable and dependent on regional climate, post-fire vegetation, catchment physiography, and the complexity of water flow pathways and below-ground water storage reservoirs (Maxwell, Call, & Clair, 2019; McDonnell et al., 2018).

5 | CONCLUSION

The data used in our study provided a rare and unique opportunity to compare and contrast the short- (1–7 years post-fire) and longer-term (35–41 years post-fire) effects of wildfire and post-fire land management on catchment hydrological processes in the EEF in the state of Washington, USA. Consistent with our expectation, we found that annual streamflow, peak flows, low flows, and runoff ratios were elevated immediately after the fire in all three of the burned catchments. However, surprisingly we found evidence that streamflow and runoff ratios remained elevated 35–41 years after the fire in the catchment that received no post-fire land management, while the catchments that were salvage-logged and seeded had recovered hydrologically. These findings have important implications, given the widespread agreement that annual area burned by wildfires is likely to continue to increase in parts of the western USA, necessitating greater decisions about post-fire land management (Dennison, Brewer, Arnold, & Moritz, 2014; Marlon et al., 2012; Westerling, 2016). As such, land managers need a better understanding of both the short- and long-term responses to their decisions if they are to successfully balance the range of trade-offs. It is clear from our study, and others, that the responses are complex and the longevity of effects remain uncertain. To disentangle some of these complexities, we must continue to compare and contrast the effects of wildfire and post-fire land management over a broader range of regions and time scales.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are in preparation by R. N. for submission to the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) Hydrologic Information System (HIS) HydroClient portal.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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