

University of Nevada, Reno

Wildfires Impacts on Spring Flows and Summer Low Flows Across the Western United States

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ABSTRACT

Forested watersheds supply essential drinking water to much of the western United States. In recent years, forest fires have increased in size, frequency, and severity, and have climbed to higher elevations into the seasonal snow zone. Most previous work focused on annual scales of hydrologic response after a forest fire and indicated increased water yields. However, effective water management requires understanding seasonal flow patterns, so it is critical to understand how forest fires impact both seasonal high and low flows. I investigated post-fire changes in high and low flows in watersheds across the western U.S. Using multiple linear regression to account for interannual climate variability, I quantified post-fire changes in the 7-day summer low flow, the 7-day spring peak flow, and the timing of the freshet. This study includes 95 watersheds that were burned between 2000 to 2020 and 156 unburned control watersheds. Watersheds were disaggregated based on aridity, percent burned area, and snowmelt contribution. Our results show significant increases in summer low flows and spring peak flows for the first five years after a fire. The post-fire freshet occurs 7 days earlier in snow-dominated watersheds compared with unburned watersheds. “Wet watersheds,” where mean annual $PET/P < 1$, have a significant post-fire residual increase in summer low flows whereas “dry watersheds,” where mean annual $PET/P > 1$, do not show any significant post-fire increases. Snow-dominated watersheds have a significant increase in summer low flows for at least the first six years after a fire whereas rain-dominated watersheds only show a significant increase for the first two years after a fire. Post-fire changes to summer low flows are amplified by the percentage of the watershed burned, especially in snow-dominated watersheds. Thus, disaggregating watersheds based on characteristics such as

aridity, percent basin burned, and snowmelt contribution to annual flow is crucial for understanding post-fire hydrology on a regional scale. For instance, earlier snowmelt timing affects reservoir management for flood risk reduction whereas changes in summer low flows affect management for water storage, and environmental flows. For managers, shifts in high and low flows change the timing of flood operations and preparedness of summer drought conditions. Thus, for effective water management, we must not only understand how extremes of the hydrographs change after fires, but also how they vary across watersheds.

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CHAPTER 1. INTRODUCTION

More than two-thirds of the western United States rely on forested areas for their water supply (T. C. Brown et al., 2008a). The forests serve as a natural filtration system and storage for water, ensuring high-quality water for downstream populations. Forested land disproportionately supplies over 450 billion $\text{m}^3 \text{ yr}^{-1}$ of surface water supply across the West (Liu et al., 2022). Local municipalities are taking steps to protect and maintain their forested water supply, especially in times of elevated water scarcity (Seattle Public Utilities, 2011). Climate change and land cover change pose a challenge to managing this water supply. Climate projections predict decreased instream flows and groundwater storage, especially in the western U.S., yet these predictions do not incorporate water-related risks due to the reduction in forests due to urbanization and wildfires (T. C. Brown et al., 2019).

Moreover, much of the stored precipitation in forests falls as snow; these western mountainous regions act as frozen reservoirs to sustain streamflow and recharge aquifers during the dry summer months. Forests and snow provide key feedback loops contributing to the variability in snow accumulation, snowmelt, vegetation growth, and soil moisture (Bales et al., 2006; Veatch et al., 2009). The conveyance of the runoff from forested mountains to urban municipalities is a multi-billion-dollar operation of snow forecasters, reservoir operators, forest managers, and many miles of hydrologic infrastructure (Costanza et al., 1997; Rhoades et al., 2018; Siirila-Woodburn et al., 2021).

Wildfires pose an alarming risk to future water supply and infrastructure since in the past two decades forest fires have exponentially increased in size, frequency, severity, and elevation (Abatzoglou et al., 2021; Abatzoglou & Williams, 2016; A. L. Westerling

et al., 2006; A. L. R. Westerling, 2016). Climate change has caused higher vapor pressure deficits, earlier snowmelt, and hotter summers. These altered processes have simultaneously affected water supply from reduced snowmelt as well as intensified and multiplied forest fires (Gergel et al., 2017; Siirila-Woodburn et al., 2021). Heightened debris flows, instream sedimentation, altered vegetative water use, stream chemistry, and snowpack dynamics are only some of the profound ramifications of escalated forest fire regime (Siirila-Woodburn et al., 2021).

Three altered processes: evapotranspiration, interception, and infiltration affect post-fire streamflow. Primarily, the reduction of evapotranspiration due to burned vegetation matter and decreased leaf area allows for more water availability for streamflow in the terrestrial water budget (Collar et al., 2022; Lavabre et al., 1993; Maina & Siirila-Woodburn, 2020). Burned canopies reduce interception loss. In turn, more precipitation, particularly snow, can accumulate on the ground and contribute to greater streamflow magnitudes (Boisramé et al., 2019; Harpold et al., 2014). Diminished infiltration rates due to hydrophobic soils and ash layers can lead to increased surface ponding and surface runoff. An elevated risk of post-fire flash flooding and debris flows can follow forest fires (Ebel & Moody, 2017; Martin & Moody, 2001). Fire impacts on hydrologic processes can vary due to burn severity, annual climate, aridity, soil type, elevation, and many other interacting watershed characteristics resulting in disparate streamflow response (Hallema, Sun, Bladon, et al., 2017). Studies have found that annual and seasonal water yield can increase by more than 20% after a fire (Hallema et al., 2018; Kinoshita & Hogue, 2015a; Moeser et al., 2020). Yet, in arid watersheds, streamflow has decreased after a wildfire (Biederman et al., 2022). Meteorologic variability also

complicates our understanding of the hydrologic response. Wet and dry years can act to amplify or mutate post-fire streamflow response in the same watershed (Biederman et al., 2022; Coombs & Melack, 2013; Kinoshita & Hogue, 2015b). Understanding how forest fires impact the magnitude and predictability of western U.S. streamflow is imperative for the management of water resources (Siirila-Woodburn et al., 2021; Wine et al., 2018).

Chapter 2 of this thesis aims to understand how three key streamflow metrics alter in magnitude and timing after a fire. We focus on the minimum 7-day flow during June, July, August, September, October, and November (Summer Low Flow); the maximum 7-day flow during April, May, June, and July (Spring Peak Flow); and the timing of the Spring snowmelt streamflow pulse (Date of Freshet). These three metrics represent valuable criteria for watershed dynamics and reservoir operations. They help regulate environmental flows, flood control, and spring growth. Moreover, this chapter focuses on a novel attempt at detecting post-fire hydrologic response using time-trend analysis methodology. While most disturbance studies focus on annual to seasonal streamflow response, we uniquely focus on metrics with a daily to 7-day time scale. We sought to answer 1) Does the 7-day summer low flow and the 7-day spring peak flow change after a fire, 2) Does the timing of the freshet shift to earlier or later after a fire, and 3) How do physio-climatic characteristics like the area burned, aridity, and snowmelt contribution control the magnitude and direction of post-fire hydrologic response? We find that summer low flows and spring peak flows increase, while the date of freshet occurs earlier for at least 15 years after a fire. This research adds to the rich literature on forest fire disturbance hydrology (Beyene et al., 2021; Hallema et al., 2018), and provides nuance to post-fire hydrologic variability based on climatic and physiographic controls.

Moreover, this work provides empirical nuance to the notion that forest fires will increase summer low flows and spring flows. Future climate projections in the western U.S. indicate increases in water scarcity due to rising temperatures and varied precipitation regimes (Overpeck & Udall, 2020; Siirila-Woodburn et al., 2021). The uncertainty caused by disturbances like forest fires further compounds the challenges in securing future water supply (Ball et al., 2021; Bladon et al., 2014; Martin, 2016). Incorporating these findings in future water and climate projections is crucial for the sustainable management of water resources and building resilience to water-related risks (Robinne et al., 2021). By understanding these effects, we can better prepare for and address the implications of climate change, forest fires, and their potential consequences on water availability and management.

CHAPTER 2. PERCENT BURNED, ARIDITY AND SNOWMELT CONTRIBUTION CONTROL LOW AND PEAK FLOW RESPONSE TO FOREST FIRE

2.1 Abstract

Forested watersheds supply essential drinking water to much of the western United States. In recent years, forest fires have increased in size, frequency, and severity, and have climbed to higher elevations into the seasonal snow zone. Previous work focused on annual scales of hydrologic response after a forest fire and indicates increased water yields. However, effective water management requires understanding seasonal flow patterns, so it is critical to understand how forest fires impact both high and low flows. We investigated post-fire changes in high and low flows in watersheds across the western U.S. Using multiple linear regression to account for interannual climate variability, we quantified post-fire changes in the 7-day summer low flow, the 7-day spring peak flow, and the timing of the freshet. This study includes 95 watersheds that were burned between 2000 to 2020 and 156 unburned control watersheds. Watersheds were disaggregated based on aridity, percent burned area, and snowmelt contribution. Our results show significant increases in summer low flows and spring peak flows for the first five years after a fire. The post-fire freshet occurs 7 days earlier in snow-dominated watersheds compared with unburned watersheds. “Wet watersheds,” where $PET/P < 1$, have a significant post-fire residual increase in summer low flows whereas “dry watersheds,” where $PET/P > 1$, do not show any significant post-fire increases. Post-fire changes to summer low flows are amplified by the percentage of the watershed burned,

especially in snow-dominated watersheds. Snow-dominated watersheds have a significant increase in summer low flows for at least the first six years after a fire whereas rain-dominated watersheds only show a significant increase for the first two years after a fire. Disaggregating watersheds by aridity, percent basin burned, and snowmelt contribution is crucial for understanding post-fire hydrology on a regional scale. For effective water management, we must not only understand how extremes of the hydrographs change after fires, but also how they vary across watersheds.

2.2 Introduction

Rising global temperatures and drought conditions have caused forest fires to increase in size, severity, and frequency (Abatzoglou & Williams, 2016; Siirila-Woodburn et al., 2021; A. L. Westerling et al., 2006; A. L. R. Westerling, 2016). In the last 40 years, the western United States has seen a 1,150% increase in forest fires. Increases in fuel aridity, vapor pressure deficit, and earlier snowmelt have exponentially intensified and multiplied forest fires (Abatzoglou et al., 2021). In the past three decades, wildfires have affected ~11% of the total stream length in the western U.S. (Ball et al. 2021). Forest fires have consequential impacts on the hydrologic systems including debris flows, instream sediment, altered vegetative water use, stream chemistry, and snowpacks (Bladon et al., 2014; Siirila-Woodburn et al., 2021). Forested watersheds supply >50% of the freshwater to the continental United States (T. C. Brown et al., 2008b; Liu et al., 2021), where water resource managers rely on the predictability of upstream watersheds to direct reservoir releases and water allocation (Mateus & Tullos, 2017; Siirila-Woodburn et al., 2021). Future climate projections for the western U.S.

estimate increasing water scarcity due to rising temperatures, varied precipitation regimes, and diminished snowpacks (Overpeck & Udall, 2020; Siirila-Woodburn et al., 2021), moreover disturbances like forest fires make water supply projections more uncertain (Hallema, Sun, Bladon, et al., 2017; Martin, 2016). Understanding the impact of wildfires on upstream watersheds is important to the sustainability of downstream water resources and readiness to adapt to water-related risks (Bladon et al., 2014; Robinne et al., 2021).

Wildfires can drastically impact core hydrological processes, including runoff, evapotranspiration, interception, and infiltration. These processes affect the magnitude and timing of streamflow, yet the direction of the hydrologic change is variable (Goeking & Tarboton, 2020a; Hallema, Sun, Bladon, et al., 2017). In many environments, streamflow can increase after a forest fire (Hallema, Sun, Caldwell, et al., 2017; Hampton & Basu, 2022; Helvey, 1980; Lavabre et al., 1993; Saxe et al., 2018; Williams et al., 2022; Wine et al., 2018). Other forest disturbances like timber production and bark beetle infestation can also lead to increases in streamflow (Bosch & Hewlett, 1982; A. E. Brown et al., 2005; Buma & Livneh, 2015; Pugh & Gordon, 2013). However, regional physio-climatic differences cause variability in post-forest hydrologic response (Biederman et al., 2022; Hallema, Sun, Bladon, et al., 2017; Maina & Siirila-Woodburn, 2020). Physical differences like drainage area, topography, and vegetation can buffer or intensify the post-fire water budget modification (Blöschl et al., 2007; Buma & Livneh, 2015; Collar et al., 2022). Moreover, the burned area of the basin can act as a threshold to observed changes in streamflow. Previous studies have found that approximately 20% of a

watershed must have been burned to detect a streamflow response (Hallema, Sun, Caldwell, et al., 2017; Williams et al., 2022; Wine et al., 2018).

The characteristics of forest fires are changing. Not only are they larger and more severe, but fires are increasing in elevation (Moritz et al., 2012; Morton et al., 2013, Alizadeh et al., 2021). As high-elevation fires advance into the seasonal and ephemeral snow zone (Gleason et al., 2019; Hatchett et al., 2023), there are consequential impacts on the accumulation, ablation, and energy balance of snowpacks for years to decades after the fire (Gleason et al., 2013; Kampf et al., 2022). Reduced interception due to a burned canopy can lead to increased snow accumulation during a storm (Maxwell et al., 2019; Micheletty et al., 2014; Moeser et al., 2020; Troendle & King, 1987), however, decreased canopy cover can increase incoming solar radiation of the surface snowpack, leading to increased radiative forcing and higher melt rates (Gleason et al., 2019; Harpold et al., 2014; Smoot & Gleason, 2021; Veatch et al., 2009). The shedding of black carbon and other impurities on snow decreases the surface albedo of the snow. This contributes to intensified incoming short-wave radiation, increasing snowmelt and leading to earlier snow disappearance (Gleason et al., 2013; McGrath et al., 2023). Decreased peak SWE reduces meltwater input for high and low flow streamflow, and earlier snow disappearance shifts this meltwater pulse to earlier in the year (Fritze et al., 2011; Siirila-Woodburn et al., 2021; Stewart et al., 2005a). Yet, the downstream hydrologic impacts of forest fires in the seasonal snow zone are not quantified on a large scale.

Not only can altered watershed processes like interception, infiltration, and evapotranspiration affect the hydrologic response, but climatic and seasonal shifts can also mask or exacerbate the effects of disturbance on streamflow (Zhao et al., 2010a).

Aridity can play an important role in mitigating watersheds postfire response. Warmer and more arid watersheds can experience a decrease in streamflow magnitude after a disturbance (Biederman et al., 2022; Goeking & Tarboton, 2022), whereas wetter, energy-limited watersheds like the Pacific Northwest and some semi-arid Mediterranean climates saw increases in annual streamflow by 200% - 1000% of normal (Hallema, Sun, Bladon, et al., 2017). Not only can regional climatic patterns affect hydrologic responses, but season-to-season and year-to-year climate trends can affect hydrologic responses. (Biederman et al., 2022; Maina & Siirila-Woodburn, 2020; Ren et al., 2021). The convolution of weather variability and vegetation change proposes a challenge in disturbance studies. In time-trend analysis studies, empirical models can account for the correlation between climate and streamflow to determine the hydrologic contribution of disturbance (Biederman et al., 2022; Goeking & Tarboton, 2020a; Williams et al., 2022; Zhao et al., 2010a).

Wildfires are increasing in all of the major western U.S. river basins, so it is imperative to large-scale studies to understand how these disturbances impact the region as a whole (Williams et al., 2022). Large-sample hydrology can provide alternative hypotheses and regionality to hydrologic disturbance to allow for more nuanced recommendations for water resource management (Goeking & Tarboton, 2022a; Gupta et al., 2014). However, not many large-scale studies have focused on low flows and peak flows (Beyene et al., 2021; Boisramé et al., 2019; Kinoshita & Hogue, 2015b). Most disturbance studies focus on total annual water yield and the runoff ratio, in part, because these aggregated streamflow metrics have less interannual variability (Carlisle et al., 2017). Few studies have focused on both low flows and peak flows. These annual

extremes of the hydrograph provide essential ecosystem services. Low flows are important for many aquatic species, regulating the stream temperatures and driving environmental flows for reservoir operators (Hammond et al., 2022; Pournasiri Poshtiri et al., 2019). The timing and magnitude of spring peak flow provide key services that signal the beginning of the growing season in many snow-dominated ecosystems (Olden & Poff, 2003; Stewart et al., 2005a). Knowing the magnitude and timing of peak flows is vital for flood mitigation and the regulation of reservoir levels. Few studies have found that post-fire low flows increase by 20% to 5,000% with larger uncertainty and variation between studies (Beyene et al., 2021; Boisramé et al., 2018; Kinoshita & Hogue, 2015). Nonetheless, how these essential streamflow metrics change with wildfire is not well understood. There is a lack of work to understand if hydrologic disturbance due to wildfire is visible not only for annual aggregated streamflow metrics but also for important sub-seasonal to weekly streamflow metrics.

This study aims to understand how low flows and peak flows change after a forest fire across the western United States. At a regional scale, we aim to quantify the change in minimum 7-day low flow, maximum 7-day peak flow, and the change in the timing of spring snowmelt runoff (date of Freshet). We utilized time-trend analysis with seasonal precipitation, temperature, and evapotranspiration data to control for weather variability. Additionally, I evaluated how subregional-scale and watershed-scale differences like the percentage burned, aridity, and snowmelt contribution.

Our hypotheses are:

- H1 –Low flows and peak flows to increase across the western U.S.;
- H2 – The timing of the freshet will shift earlier in the water year;

- H3 – Hydrologic changes will vary regionally based on watershed characteristics like snowmelt contribution, aridity, and percent burn.

2.3 Research Methods

2.3.1 Research Area

Our research areas included 95 burned and 156 unburned watersheds in the western United States. We selected 95 burned watersheds for wildfires that occurred during the years 2000 – 2020. These basins spanned various topographic and climatic conditions contributing to the major drainages of the Columbia, Great Basin, Upper Colorado, and Lower Colorado. The burned watershed drainage areas ranged from 25 km² to 7,161 km².

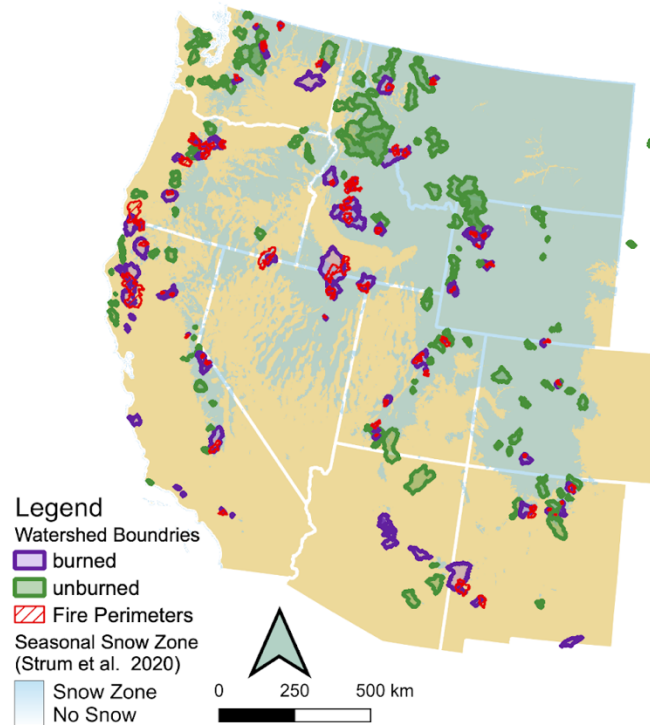


Figure 1. Map of Burned (purple) and Unburned (green) watersheds with the forest fire perimeters.

2.3.1 Watershed Selection

Streamflow and watershed perimeter data were gathered through the United States Geological Survey (USGS) Geospatial Attributes of Gages for Evaluating Streamflow, version II (GAGES II) dataset (Falcone, 2011, USGS 2022). The GAGES II dataset includes USGS streamflow gages that have 20+ years of complete data or have been active since 2009. To select comparable watersheds, we followed the watershed selection methodology of Williams et al 2022. We selected the GAGES II reference gages, defined by watersheds that are minimally disturbed and have near-natural flow. For a greater sample size, we selected non-reference gages with a USGS hydrologic disturbance index

of ≤ 10 and ≤ 1 dam in which the dam's storage was less than 10% of the annual total streamflow (Falcone, 2011; Williams et al., 2022). We classified the western U.S. as watersheds that fell west of 102° W longitude. Within this region, we selected gages that were active since the 2017 water year and watersheds had to have streamflow data for at least 80% of the days for each half of the water year from 1959 to 2022. Before determining if gages had sufficient continuous data, missing data were filled in using linear interpolation for a maximum of 10 missing days in each gage data time series. To eliminate any intermittent or ephemeral streams, we removed watersheds with a mean annual stream of 0 CFS for any year in the period of record or had more than 5 years of 0 CFS as the minimum 7-day low flow.

To limit variability caused by other pyromes, like differences due to brush fires compared to forested fires, we focused analysis on only fire that had occurred in forested vegetation. We used the USGS National Landcover Database (NLCD) to calculate each basin's percentage of forested area. We selected the NLCD landcover dataset for the years 2001, 2004, 2006, 2008, 2011, 2013, 2016, and 2019 to create a fractional forest cover data set for each year across the western United States. We aggregated each dataset up to 1 km resolution and selected the maximum forest cover value at each pixel across all years. We defined this aggregate maximum forest cover map as our pre-fire conditions. We selected watersheds with $\geq 25\%$ forest cover (Williams et al., 2022).

We distributed burned watersheds and unburned watersheds using the Monitoring Trends in Burn Severity dataset (MTBS). We used MTBS fire perimeter data to define burned watersheds as basins that had burned $>5\%$ in one incident from 2000 – 2020. In many watersheds, more than one burn occurred in the period of record, we selected the

fire incident with the largest burned area in the watershed. We considered the fire's ignition date as the fire year.

Burned watersheds had to have at least 15 years of continuous pre-fire data to representatively capture pre-fire streamflow conditions. In unburned watersheds and pre-fire burned watersheds, annual precipitation, and streamflow must have a mean Pearson's Correlation Coefficient of >0.5 to select watersheds in which climate largely controls pre-fire streamflow variability instead of unknown watershed characteristics like long-term groundwater sources. After filtering for environmental and data criteria, we were left with 95 burned watersheds. We removed any unburned gages that fell outside of the minimum and maximum mean annual precipitation and temperature of the burned gages.

2.3.2 Hydrologic Metrics

In snowy montane watersheds, streamflow follows a seasonal pattern, with low flows during the late summer to early winter, and then a rapid increase in discharge during the spring and early summer during the snowmelt season (Cayan & Peterson, 2013). This research evaluates how the magnitude and timing of high and low flows change after a forest fire. These metrics include the minimum 7-day low flow, the maximum 7-day peak flow, and the day of spring melt onset (date of freshet).

Daily streamflow data were collected from the USGS National Water Information System during the available water years from 1980 to 2022 using the R dataRetrieval package (De Cicco et al., 2018; U. S. Geological Survey, 1994). We normalized daily streamflow by the watershed contributing area to reduce variation due to the differences among watershed sizes. Thus, daily streamflow is presented in units of mm per day (Eng

et al., 2019; Hammond et al., 2022). To minimize daily variability and maintain streamflow at a sub-monthly scale, we calculated the 7-day moving mean streamflow.

To characterize the low-flow recession period during the summer months, we calculated the minimum 7-day streamflow during the months of June, July, August, September, October, and November (Pournasiri Poshtiri et al., 2019). To measure peak flow, we computed the maximum 7-day streamflow during the months of April, May, June, and July for snow-dominated watersheds. This metric aimed to characterize the peak stream flow during the spring snowmelt pulse (Stewart et al., 2005a). We will further refer to these two metrics as summer low flow and spring peak flow, respectively.

The spring snow melt pulse, specifically known as the freshet, signals when summer low flows transition to spring high flows (Cayan et al., 2001). Importantly, the timing of freshet is key for water operations and ecohydrological signals (Cayan et al., 2001; Stewart et al., 2005b). We followed the Fritze et. al 2011 method to identify the timing of the freshet. First, we calculated the cumulative departure from the mean annual flow starting at the beginning of the water year. The date of freshet was defined as the date of the global minimum between days 150 and 250 of the water year. By the definition of the freshet, snow melt onset, we limited our calculations to those watersheds that are mostly snow-dominated. We defined snow-dominated watersheds as basins where the summation of the cumulative departure from the annual mean for days between 150 and 250 is less than 1 (Fritze et al., 2011).

2.3.3 Time-Trend Analysis

Time-trend analysis is used to determine streamflow change after a forest disturbance (Biederman et al., 2015; Goeking & Tarboton, 2022a; Williams et al., 2022; Zhao et al., 2010b). Time-trend analysis develops an empirical regression model for a watershed or group of watersheds to predict streamflow using climate parameters like precipitation, temperature, and evapotranspiration during the pre-disturbance period. Subsequently, the regression model predicts the pre-and post-disturbance streamflow. Residuals were calculated from the observed and predicted datasets. Differences in the pre-and post-fire residuals indicate the influence of the disturbance. Although previous studies have used annual and monthly scales, we have chosen to apply this method to weekly to daily time scales. (Biederman et al., 2015; Goeking & Tarboton, 2022a; Zhao et al., 2010b). Computationally, we followed the Williams et. al 2022 methodology for model selection.

2.3.3.1 Meteorologic Predictor Data

Meteorological data were obtained using monthly means and totals from gridMET at 4-km resolution for each water year from 1960 to 2022 (Abatzoglou, 2013). These data included total precipitation (mm), daily maximum temperature (°C), daily minimum temperature (°C), and reference ET (mm). Additionally, we used the 1-and 2-year standardized precipitation evapotranspiration index (SPEI) in the gridMET dataset. The SPEI provides a daily drought index for 1 to 2 years leading up to that day where positive values signal a wetter period and more negative values signal a drought period. Since each basin's empirical model was not auto-regressive, the previous year's climate did not affect the current year's streamflow. In consequence, the inclusion of SPEI 1 and 2 years

aimed to address the concept that low flow variability can be influenced by time-lagged and long-term drought processes (Eng et al., 2019; Eng & Wolock, n.d.; Hammond et al., 2022). The inclusion of SPEI in our time-trend analysis improved many of the watersheds' regression AIC scores.

For each water year, we used the total monthly precipitation for October to December (OND), January to March (JFM), April to June (AMJ), and July to September (JAS) and took the mean of each of the four other climate variables. Following the aggregation method of Williams et al. (2022), we then aggregated the three months using the sum (precipitation and ET) and means (temperature and SPEI). For longer periods during the year, aggregations of multiple months were abbreviated as ONDJFM, ONDJFMAMJ, ONDJFMAMJJAS, JFMAMJ, JFMAMJJAS, and AMJJAS. There were 50 possible aggregations of climate parameters to predict each hydrologic metric. After aggregation, we normalized each possible parameter to better compare with the relatively small magnitudes of each hydrologic metric.

2.3.3.2 Burned Watersheds Model Selections

We calculated a Pearson's correlation test ranking each potential climate predictor with the streamflow metric from the highest absolute correlation coefficient to the lowest. We constructed a simple linear regression model with the most correlated parameter as the single predictor and trained each model for the pre-fire years of record. AIC score quantified model performance. We determined the meteorological variable most correlated with the old model's residuals and subsequently included that variable as an additional additive parameter to the old model. This model was then considered the "new

model.” If the new model’s AIC score was lower than the previous model’s then the parameter was retained in the model formula (Williams et al., 2022). Through this stepwise model selection technique, we continued the process of including correlated parameters until AIC scores did not decrease by 2. The final model included all the parameters that resulted in the lowest AIC score. The residuals were estimated with the following equation for every watershed during the pre-and post-fire period

$$Y_{Observed} = X\beta + \epsilon,$$

Equation 1.

where X is a $n \times p$ matrix with n number of observations, p number of climate parameters, and β is a vector of p parameters. Given this, $X\beta$ is the estimated streamflow response, based on climate alone, and ϵ is a vector of n residuals, which is estimated by

$$\epsilon_{Residuals} = Y_{Observed} - Y_{Estimated}$$

Equation 2.

Changes due to fire are determined by the residuals: the difference between the observed hydrologic metric and the estimated hydrologic metric. These residuals are in units of standard deviations (σ) since all metrics have been standardized. We compared post-fire residuals for the individual basins with unburned basins. Moreover, we calculated the mean residual for each year following a fire across all 98 burned basins.

2.3.4 Unburned Watershed Comparison and Significance Testing

We selected 158 unburned watersheds to control for auxiliary streamflow changes that we had not accounted for in our regression models. For each burned watershed, we

randomly selected an unburned watershed to conduct a concurrent time-trend analysis. The unburned regression model was selected using the same methodology as the burned basins. The training years for the unburned basin model were the same pre-fire, training years as the paired burned basin. Additionally, missing years from the burned basin were deemed missing for the unburned basin. We drew from the same potential meteorologic variables listed for burned watersheds and calculated the mean and sum for meteorologic variables across each selected unburned watershed. We then calculated the pre- and post-fire residuals (Equation 1). We repeated this process 10,000 times, each time randomly selecting an unburned watershed. The burned basin residual change was significant if the burned residual was significantly different from the 95th percentile of the unburned residual simulations (Figure 2a). We repeated this process for each individual basin to the number of significant years of residual change.

The cross-basin comparison calculated the mean residual of each year since the fire between all 95 burned basins. We selected 95 unburned basins and trained each unburned basin model for the corresponding burned basin's pre-fire years. We calculated the mean pre-and post-fire residuals for the group of unburned basins. From 10,000 simulations, we calculated a 95th percentile of unburned basins. We additionally calculated a student's t-test to compare the burn basins residuals mean distribution with the unburned basins. Significance was determined with a p-value < 0.05 .

2.3.5 Comparison of Basin and Fire Characteristics to Hydrologic Response

To test the sub-regional variability of the streamflow metrics' residuals, we disaggregated the watersheds by key characteristics like percentage burned, aridity, and snow-to-

streamflow contribution. We determine the percent of the watershed burned through the intersection of the watershed boundaries and the vectorized MTBS fire perimeter data (Falcone, 2011; Finco et al., 2012). The long-term aridity index (PET/P) was derived from the GAGES II dataset where mean PET and P for the 30-year time period of 1971 - 2000 using the PRISM dataset (PRISM, 2014). Watersheds were classed as water-limited, dry, when $PET/P > 1$, and energy limited, wet, when $PET/P < 1$. Following Fritze et al. (2011), We classified watersheds as snow-dominated and rain-dominated. Snow-dominated watersheds were defined as having a snowmelt pulse (freshet) for $>50\%$ of all years with available data. Rain-dominated watersheds had a freshet for $<50\%$ of all years.

2.4 Results

Temporal analysis revealed that summer low flows are higher than expected based on climate drivers (P, T, ET, and SPEI) for at least the first five years after a fire for burned watersheds as compared to unburned watersheds. Moreover, the spring flows are larger and earlier than expected by climate forcings. Watershed response was modulated by aridity, fire extent, and snowmelt contribution. Less arid watersheds have a larger increase in summer low flows following a fire. These increases are further amplified in watersheds that have greater drainage areas burned. Moreover, snow-dominated watersheds affected by large wildfires have larger increases in post-fire summer low flows than rain-dominated watersheds.

2.4.1. Summer Low flows, Spring Peak flows, and Timing of Freshet vary after Wildfire

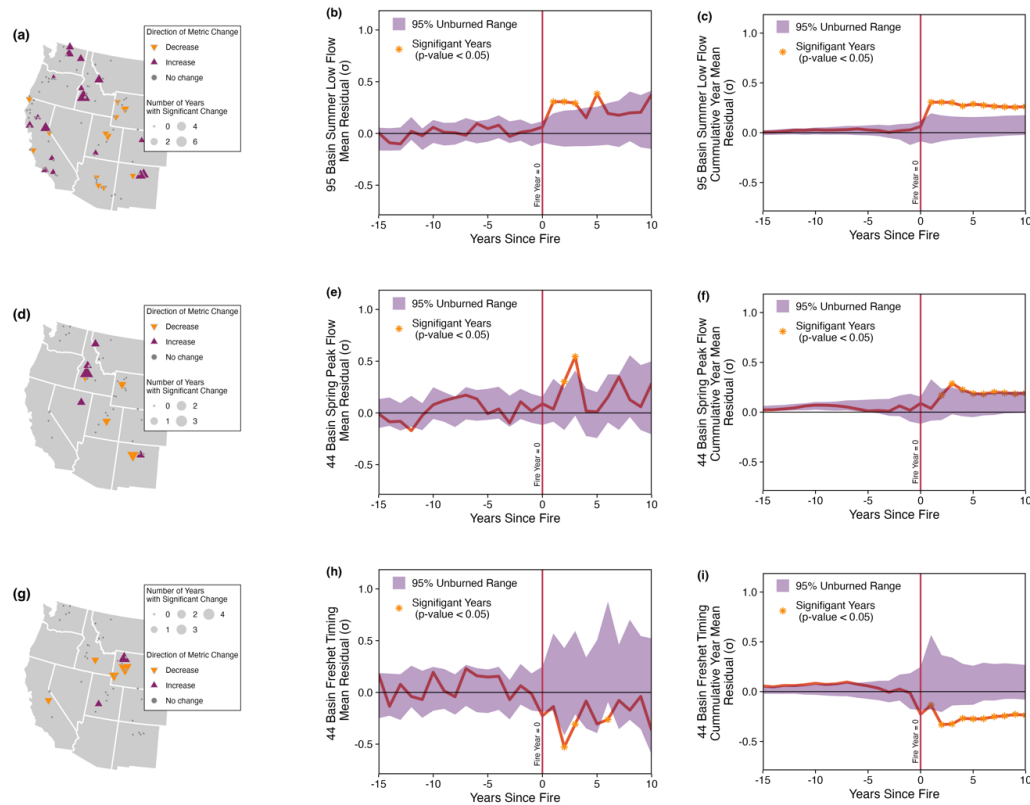


Figure 2. The effect of forest fire on each streamflow metric across the western U.S. through multilinear analysis. (a, d, g) A map of the watersheds post-fire residuals. The color indicates positive, negative, or no residual change. Symbol size reflects the number of years of significant residual change from 95% of the unburned watershed residual distribution. (b, e, h) The mean 7 residuals across selected burned watersheds. The vertical red line represents the year of fire occurrence. The shaded area shows the 95% unburned residual distribution. (c, f, i) The cumulative (multi-year) residual mean represents the mean residual across all basins and for years preceding or leading up to the fire. The stars in the time series plots (b, c, e, f, h, i) are years where the burn residual mean is significantly different from the unburned distribution (p-value < 0.05).

For summer low flows, most burned watersheds have either no change or more than one year of significant positive residual change compared to unburned watersheds

(Figure 2a). At an individual watershed scale, 20% of these burned watersheds have at least 5 years of positive residual change. Only 2% of watersheds have more than 5 years of residual decreases (Figure 2a, Table S 2). Negative low-flow residuals occurred in more arid areas like Colorado, Montana, New Mexico, Utah, Wyoming, and Southern California (Figure 2a).

As an aggregate mean, the 98 burned basins had positive low flow residuals for at least 10 years after a fire, and significant positive residuals for years 1, 2, 3, and 5 (Figure 2b). Since low flow patterns can be influenced by year-to-year variability, we considered the mean residual change across all basins for the cumulative years since the fire to observe the collective post-fire residual trend (Williams et al., 2022). The cumulative year mean for 95 burned basins was significant for the first 19 years after a fire (p -value < 0.006 , Table S 3) (Figure 2c). We chose not to calculate mean residual change for >19 years after a fire because only 5 burned watersheds have streamflow data and there is a high degree of variability. The mean summer low flow residual is 0.29σ for years 1-5 post-fire across 66 watersheds (Table 1). Further inter-basin comparisons used the cumulative year, and multi-basin mean because of the high variability amongst years and basins (Williams et al., 2022).

To address the second hypothesis: *how do spring peak flow and date of freshet alter after a fire*, we focused on only snow-dominated watersheds since these basins have discernable annual patterns of spring flow magnitude and timing as compared to rain-dominated watersheds that are largely controlled by indiscriminate precipitation events (Carlisle et al., 2017).

We focused only on snow-dominated watersheds to understand how spring melt metrics changed after a fire. Specifically, we choose to look at spring peak flow and spring snowmelt onset (date of freshet). Most individual basins showed no significant spring peak flow change. Five basins showed more than one year of positive residual change and 4 basins showed more than one year of negative residual change (Figure 2d). Although the mean residual change was positive across 44 snow-dominated watersheds, only 2nd and 3rd years since the fire was significantly positive from the unburned distribution (Figure 2e). Across all snow-dominated basins, the residual mean was 0.19σ for years 1-5 since the fire (Table 1). The cumulative year mean across all basins was significantly positive for years 2-15 (p-value < 0.05, Table S 3).

The timing of the freshet was significantly positive for 2 basins and negative for 3 basins. A positive residual signified that the timing of the freshet occurred later than just climate variability predicted, and a negative residual would signify the freshet occurred later than expected. As an aggregate, the residual freshet was negative for the first 15 years after a fire, but only significant for years 2, 3, 6, and 11 (Table S 3). The mean residual for snow-dominated watersheds was -0.27σ for years 1-5 since the fire (Table 1). Nevertheless, for an individual watershed, there was high variability between years. Single-years do show significant differences for the unburned watersheds, yet there is no geographic nor temporal pattern for the post-fire time period.

Table 1. Burned watersheds post-fire residual values in units of standard deviations (σ). Residuals for each basin are calculated time-trend analysis. The mean residuals are calculated by taking the mean across all watersheds and the cumulative mean across years.

All Basin Residual Mean (σ)

Streamflow Metric	1 – 2 Year Mean Residual	1 – 5 Year Mean Residual	1 – 10 Year Mean Residual
Summer Low Flows n = 98	0.31	0.29	0.26
Spring Peak Flows n = 44	0.17	0.19	0.19
Freshet Timing n = 44	-0.33	-0.27	-0.24

2.4.2 Aridity, Snow-dominance, and Percent Watershed Burned Effect on Post-fire

Summer Low Flows

We sought to test our third hypothesis: *whether the post-fire hydrologic response is modulated by physio-climatic factors*. We disaggregated burned watersheds by aridity, snowmelt contribution, and the percent of the watershed burned. We specifically focused on summer low flows since the metric had the largest 1–5-year mean residual.

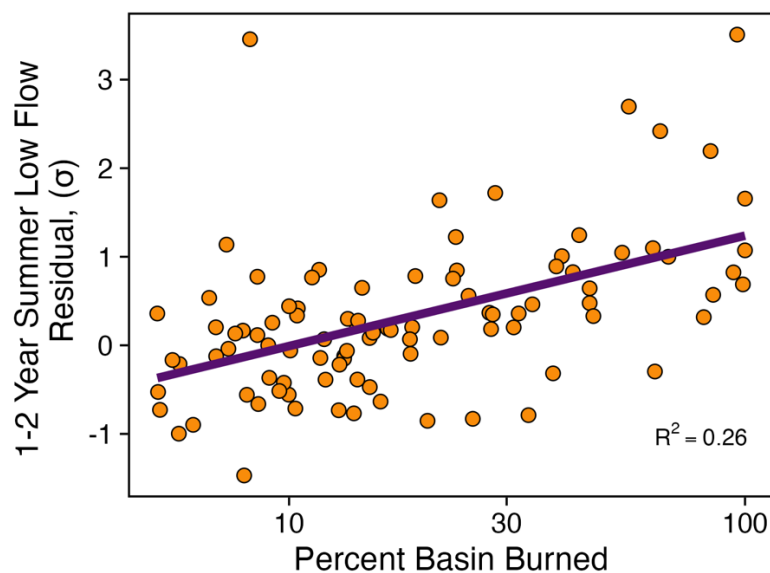


Figure 0.3. The percentage of the watershed burned has a positive relationship with the 1-2 year mean summer low flow residual, standard deviations (σ) for all 98 burned watersheds. The orange points are the mean residual for each watershed and the purple

line signifies the linear relationship between the percent watershed burned (log-scale) and summer low residual with an R^2 of 0.26, a slope of 0.018, and a p-value of < 0.001 .

Summer low flow residuals are linearly correlated significantly with the percent of the watershed burned (p-value < 0.001 , Table S 4). The 1-2 year cumulative low-flow residual mean for basins with $>20\%$ burned area is 0.75σ . This trend is amplified in basins with $>50\%$ burned area with a residual mean of 1.17σ .

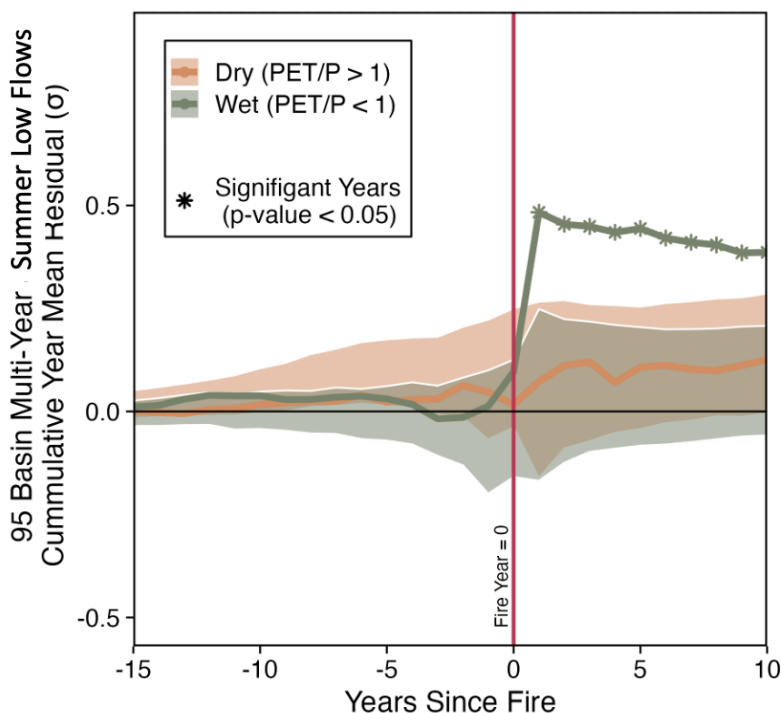


Figure 4. Aridity controls the post-fire summer low flow response. Wetter, energy-limited watersheds where $PET/P < 1$ show an increase in post-fire low flow residuals (green line), whereas drier, water-limited watersheds where $PET/P > 1$ show less of a residual increase (brown line). The vertical red line represents the fire year. The shaded area shows the 95% unburned range for both wet and dry watersheds.

Water-limited watersheds ($PET/P > 1$) showed no significant years of positive low flow residuals, whereas energy-limited watersheds ($PET/P < 1$) showed a larger positive mean residual of 0.44σ years 1-5 years since the fire (p-value < 0.001) (Figure

4). A larger residual mean suggests that wetter ($PET/P < 1$) watersheds have a larger increase in low flows than more arid watersheds ($PET/P > 1$).

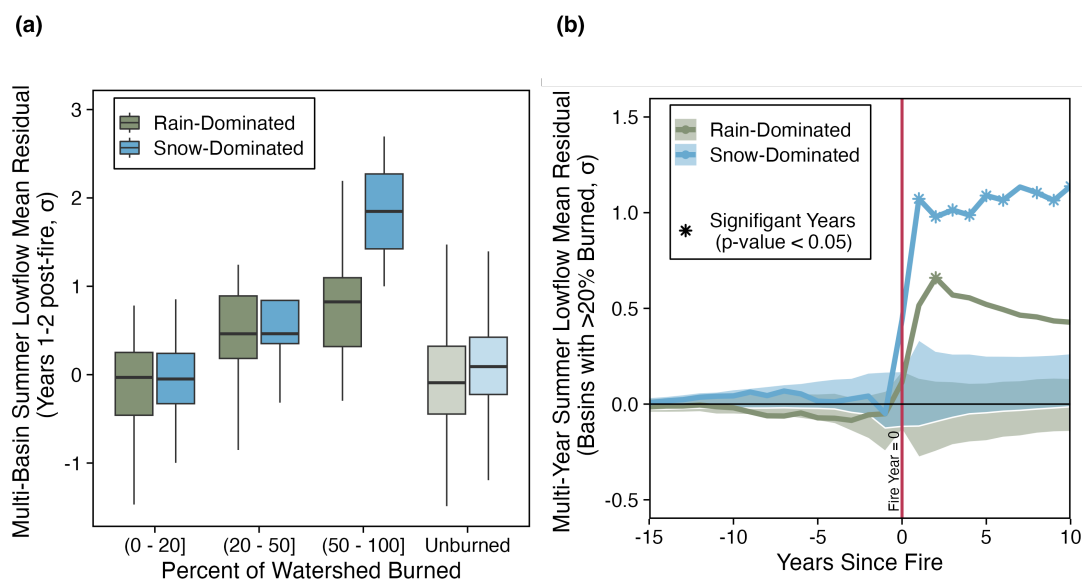


Figure 5. The effect of the percent area burned on summer low flow residuals is amplified in snow-dominated watersheds as compared to rain-dominated watersheds. (a) Boxplots of mean summer low flow residuals for years 1-2 based on 98 burned watersheds and 156 unburned watersheds. Watersheds are aggregated by the percent of the basin burned and categorized by snow-dominated or rain-dominated hydrographs. (b) The multi-year low flow residual means for all rain-and snow-dominated basins that have >20% burned area. The cumulative (multi-year) residual mean represents the mean residual across basins and for years preceding or leading up to the fire.

Both watershed classes showed no significant residual change when < 20% of the watershed has burned, yet > 20% watershed area burned both watersheds show significant mean residuals increased for years 1-2 (Figure 5). Figure 5b illustrates that the residual low flow in snow-dominated watersheds was more sensitive to the percent of the watershed burned than in rain-dominated watersheds. For watersheds that have >20% burned area (heavily burned), the summer low flow residual mean for years 1-2 in snow-dominated watersheds is 0.97σ whereas in rain-dominated watersheds residual mean was

0.67 σ (p-value < 0.05, Figure 5b). Heavily burned snow-dominated watersheds have significant low flow residuals for at least years 1-6 after a fire compared to unburned watersheds, yet rain-dominated watersheds are only significant for the first 2 years after a fire.

2.5 Discussion

2.5.1 Variability in Post-Fire Summer Low Flows, Spring Peak Flows, and Spring Freshet Timing

Through time-trend analysis, we found that the cumulative mean of the residual summer low flow for the months of June to November was 0.29 σ for years 1-5 after fire across all 95 watersheds. On average across the western U.S., summer low flows increase by 22% after being log-transformed. These results support our hypothesis and agree with previous studies that have found that low flows can increase by more than 20% after a large fire (Bart & Tague, 2017; Beyene et al., 2021; Biederman et al., 2022; Kinoshita & Hogue, 2015b; Williams et al., 2022). Summer low flows have a particularly strong sensitivity to the evaporative demand (Cooper et al., 2018). The amplified reduction of plant-evaporative demand, root water input, and interception during the summer could allow for more precipitation partitioning to streamflow (Kinoshita & Hogue, 2015b). Nonetheless, although summer low flows can increase initially, long-term, 10 – 15 years, post-disturbance revegetation can lead to decreases in summer streamflow (Moore & Wondzell, 2005; Perry & Jones, 2017).

Across all snow-dominated watersheds, the 7-day spring peak flow showed 2 years of significant positive residuals post-fire. Moreover, the mean residual change displayed a 15% increase across all snow-dominated basins for years 1-5. In snowy watersheds, spring peak flows often occur before peak ET, so the post-fire reduction of

evapotranspiration is not as impactful to spring flows as fire is on summer low flows. Williams et. al (2020) found total post-fire streamflow increased the most during the spring months of April, May, and June compared to pre-fire conditions as compared to the summer months. On the contrary, Biederman et al. (2022) found spring and winter flows either did not change or decreased after a fire. Also, post-fire peak flows were more dependent on weather than wildfire disturbance (Kinoshita & Hogue, 2015b). Although summer low flows increase, winter and spring flows are more dependent on seasonal climate patterns (Beyene et al., 2021; Biederman et al., 2015; Collar et al., 2022). In Californian chaparral forests, forest fires led to flashier and larger peak flows during the wet season, but larger, more frequent winter storms resulted in diminished increases in peak flows after the fire (Coombs & Melack, 2013). In Colorado, drier years became decoupled with precipitation variability resulting in little change in streamflow, whereas during wet years streamflow deviated from the pre-fire normal (Biederman et al., 2022; Ren et al., 2021). Moreover, the 7-day maximum peak flow could be too variable due to its fine temporal scale to capture changes in spring peak runoff. Estimating spring peak flow as a larger temporal aggregate like a 30-day mean, or a monthly total could reflect a systematic streamflow trend rather than interannual variability. Interannual climatic differences between forest fires and watersheds can result in a variable hydrologic response. Understanding what differences drive changes in streamflow allows water managers to respond after a forest fire more effectively.

We found that across all snow-dominated basins mean freshet timing shifted 7 days earlier 3 years after a fire (Fig. 6). This shift earlier could be due to the change in the energy balance of the snowpack. The reduced canopy could increase incoming solar

radiation with the additive effect of reduced albedo from black carbon impurities in the snowpack (Gleason et al., 2013; Harpold et al., 2014). The altered energy balance of the snowpack could cause snow to melt sooner resulting in an earlier date of freshet.

Modeling studies have found that peak flow timing has shifted by two weeks to a month in disturbed mountainous snow-dominated watersheds however this timing shift is hard to attribute solely to disturbance events since both studies did not control for weather or climatic trends (Buma & Livneh, 2015; Collar et al., 2022; Owens et al., 2013). Across all watersheds, the freshet had the highest mean RMSE and lowest R^2 values (Table S 1). This poor model fit hints at the difficulty of predicting the day of the year a streamflow event occurred (Eng et al., 2017). The heterogeneity of significant residual timing changes could be the result of poorly fit regression models and interannual variability (Figure S 3).

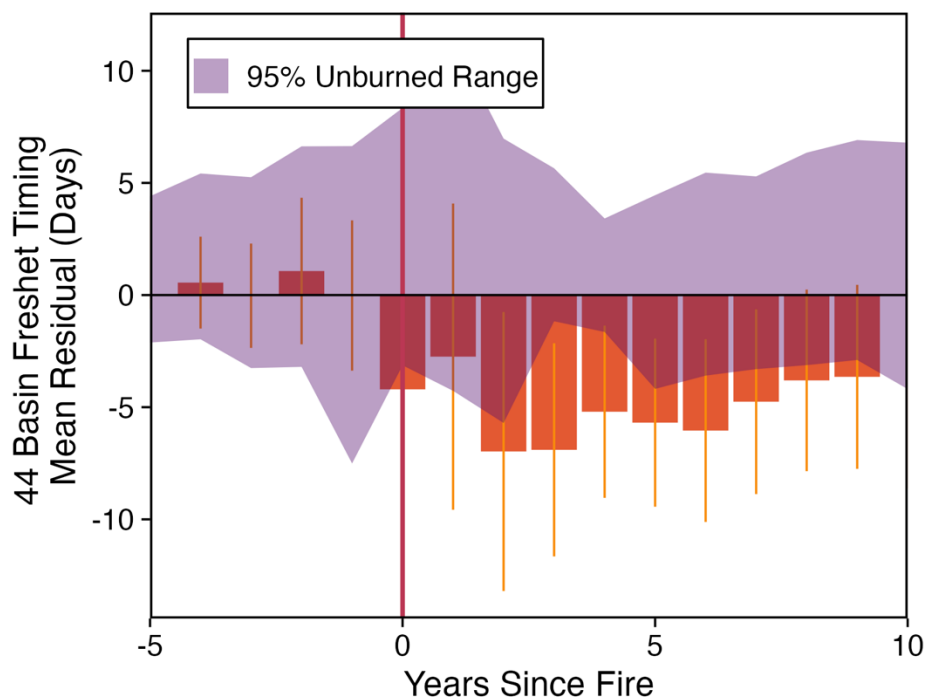


Figure 6. The multi-year mean residual for 44 snow-dominated basins is significantly negative for the first 6 years after a fire (Days). The dark bars represent the mean residual across all 98 basins and for years preceding or leading up to the fire. The yellow bars show the 95% confidence intervals around the mean residual change. The shaded area shows the 95% unburned residual distribution.

2.5.2 Percentage Burned, Aridity, and Snowmelt Contribution Control Post-Fire

Low Flow Sensitivity

All streamflow metrics had a positive correlation with the percent watershed burned for the first five years after the fire, but only summer low flows and spring peak flows have a significant relationship (p -value < 0.05, Table S 4). This finding agrees with studies that found annual water yield was positively correlated with the percent of the watershed burned (Bart, 2016; Bosch & Hewlett, 1982; Williams et al., 2022). Summer low flow residuals have the strongest correlation to the burned area (Saxe et al., 2018). However, the hydrologic response in more arid watersheds can be less sensitive to the percentage of

the watershed burn (Fig. S 6). In wetter and colder watersheds, larger burned area correlated to greater changes in the timing and magnitude of annual water yield. (Holden et al., 2012; Ren et al., 2021)

2.5.2.1 Aridity as a Driver of Post-fire Summer Low Flows

Aridity, PET/P, is a large driver of post-fire summer low flows. Wet, energy-limited, watersheds have a larger increase in summer low flows with a mean residual of 0.7σ for 1-5 year after a fire, approximately a 50% increase of the log-normal summer low flow. Dry, water-limited, watersheds showed an insignificant increase in summer low flows. This builds off previous work that finds annual water yield decreases in dry basins after a disturbance and increases in wet basins (Bennett et al., 2018; Biederman et al., 2014; Goeking & Tarboton, 2022; Ren et al., 2021). These studies found that the long-term aridity, PET/P, is a threshold for decreases in annual precipitation. Watersheds with $PET/P > 2$ exhibit decreases in post-disturbance streamflow (Goeking & Tarboton, 2022b; Ren et al., 2021). Very arid watersheds have been shown to increase in evapotranspiration due to rapid regrowth of the understory and sub-canopy, whereas wetter watersheds have decreased transpiration.

In addition to long-term aridity indexes, annual wetness or dryness can influence post-disturbance water yield. Although this study did not investigate interannual variability, studies have found that wet years can often lead to increases in annual runoff, whereas during a dry year especially in semi-arid to arid basins, runoff can decrease (Bart, 2016; Biederman et al., 2022). Moreover, wildfires have been seen to effect base-flow recession rates during periods of low antecedent groundwater further impacting low

flow magnitudes (Bart & Tague, 2017). After a wildfire, wet watersheds may be able to regulate decreases in low flows due to drought conditions like increased temperature and decreased precipitation, whereas these conditions could cause decreased low flows in dry watersheds (Goeking & Tarboton, 2022b). Summer low flows in arid basins are more sensitive to PET increases and precipitation decreases (Cooper et al., 2018). Wildfire's impact on semi-arid watersheds could mask the impact of drought conditions on summer low flows.

2.5.2.2 Post-fire Summer Low flows in Snow-dominated and Rain-dominated Watersheds

Our results show that snow-dominated watersheds have a larger increase in summer low flows than rain-dominated watersheds when more than 20% of the basin has burned. To understand the process behind the discrepancy between heavily burned snow and rain-dominated, we must understand the climatic controls of low flows between these two watershed classes (Cooper et al., 2018). Low flow elasticity is highly correlated with snow accumulation and melt in snow-dominated watersheds. Decreased snow accumulation and earlier snowmelt portend to decreased low flows, whereas larger snowpacks lead to elevated summer low flows (Barnhart et al., 2016; Godsey et al., 2014; Son & Tague, 2019; Tague & Grant, 2009). Yet, in lower elevation watersheds, low flows are less sensitive to the proportion of precipitation that falls as snow (Cooper et al., 2018; Jenicek et al., 2016; Son & Tague, 2019). The low flows in these rain and “less” snow-dominated watersheds are more sensitive to changes in precipitation and PET (Cooper et al., 2018).

The asynchrony of soil water storage and forest transpiration in part drive watershed elasticity to forest disturbance (Goeking & Tarboton, 2020b; Knighton et al., 2020). Snowmelt offers a lagged availability of soil moisture for active periods of transpiration during spring and summer months, resulting in more sensitive runoff to changes in transpiration. However, in temperate rain-dominated watersheds, winter precipitation occurs primarily during forest dormancy, so soil water storage is not influenced by changes in transpiration (Knighton et al., 2020; Robles et al., 2020). Moreover in rain-dominated watersheds, winter precipitation contributes to flows during the wet season whereas in snow-dominated watersheds, the snow delays the input of winter precipitation to the spring melt season future contributing to spring and summer flows.

Forest fire and its extent impact climatic controls differently and uniquely impact the post-fire sensitivity of summer low flows. Many studies have found that the reduction of interception from disturbance decreases sublimation and increases snow accumulation (Gleason et al., 2019; Hammond et al., 2023; Pugh & Gordon, 2013; Varhola et al., 2010). The interception and subsequent loss from sublimation from snowfall can be far larger than the evaporative loss due to canopy interception from rainfall events (Link et al., 2004; Lundberg & Halldin, 2001; Roth & Nolin, 2017). The observable increases in summer low flows in both rain- and snow-dominated basins can be in part attributed to the reduction of canopy interception (Stednick, 1996), yet the larger residual change in snow-dominated watersheds where >20% of the basin has burned can be due to the larger reduction in canopy loss and sublimation. Snow-dominated summer low flows are more sensitive to basin canopy loss than rain-dominated watersheds. As fires increase in extent

and elevation, the elasticity of summer low flows to disturbance is essential to understand, especially in snow-dominated watersheds.

2.5.2.3 Understanding the Interaction between Snow-melt Contribution and Aridity

Nonetheless, watershed characteristics like percent of the watershed burned, aridity, and snowmelt contribution do not exist singularly. Watersheds can be snow-dominated, yet also very arid. Examining how watershed characteristics interact is crucial for the understanding of the driving or limiting mechanism of post-fire hydrologic response. In Supp. Figure 9, we plotted the mean summer low residual response for years 1-5 after a fire sorting watershed as “Wet Snow,” “Dry Snow,” “Wet Rain,” and “Dry Rain.” Watersheds were classified by the long-term aridity where “wet” was $PET/P < 1$ and “dry” when $PET/P > 1$ and then by snowmelt contribution “snow”-dominated or “rain”-dominated. In watersheds burned $>20\%$, we found that snow-dominated watersheds regardless of aridity had a high mean summer low residual for years 1-5 (Fig S 9), although small sample sizes between watersheds classification limits statistical analysis. This pattern suggests snow-dominated hydrographs will increase in summer low flows, especially in climates where $PET/P < 1$, whereas rain-dominated hydrographs do not see an increase in post-fire low flows (Figure S 8). Three primary mechanisms are controlled by differences in aridity and snow-melt contribution: evaporative demand, interception loss, and timing precipitation input. More arid watersheds have higher evaporative demand. Snow-dominated watersheds experience larger precipitation input losses due to interception. Additionally, snow acts as a frozen reservoir, storing precipitation until the spring melt season when there is prolonged aggregated moisture input into the watersheds. The delayed input can sustain spring and summer streamflow. In rain-

dominated watersheds, winter precipitation occurs intermittently and immediately contributes to water availability. How these mechanisms can amplify or diminish each other's contribution to the water budget after a fire is essential to understand post-fire hydrology. Supplemental Figure 9 demonstrates that the hydrologic mechanisms in snow-dominated watersheds have a greater post-wildfire response in summer low flows. We see that regardless of watersheds' aridity, snow-dominated watersheds have larger residual low flows, suggesting that interception and timing of meltwater input largely control post-fire low flow surplus.

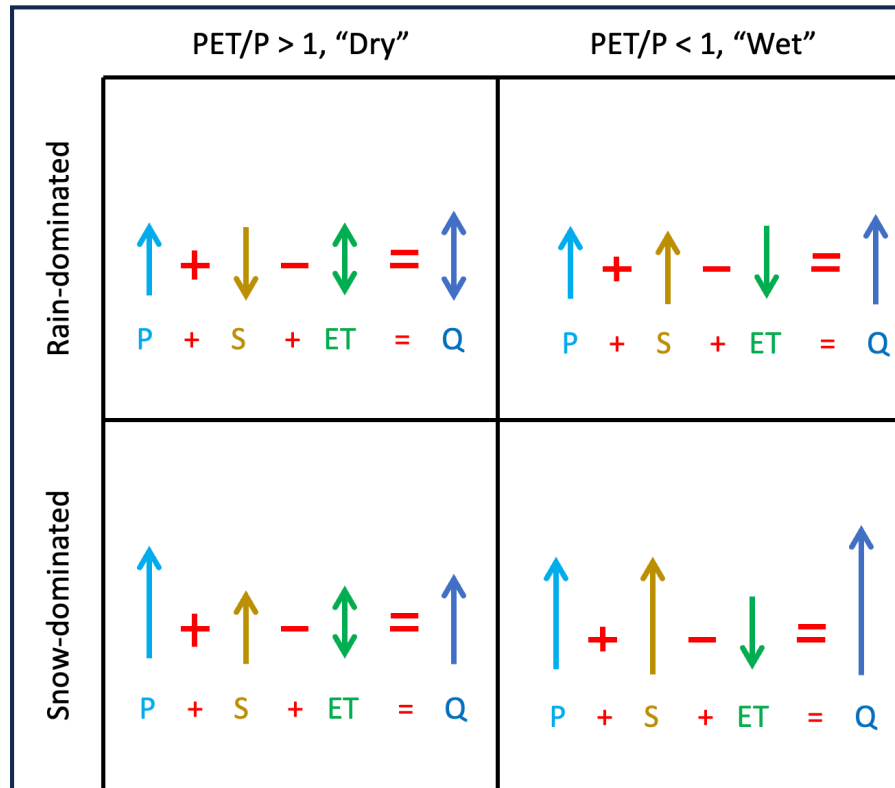


Figure 7. A conceptual diagram outlines the post-fire hydrologic change for simple water budgets in four types of watershed classifications: rain-dominated and “dry”, rain-dominated and “wet”, snow-dominated and “dry”, and snow-dominated and “wet.” The watershed budget is precipitation (P), soil water surplus (S), evapotranspiration (ET), and streamflow (Q). The direction of the arrows indicates an increase (up) or decrease (down). The size of the arrows shows the magnitude of the change after a fire.

2.5.3 Limitations

The primary source of uncertainty in this study is the time-trend analysis methodology itself. Time-trend analysis relies on the core assumption that residual values are solely attributed to the disturbance occurrence. Conversely, all naturally occurring processes in the watershed are assumed to be accounted for in the pre-fire empirical model. However, the empirical model could not separate hydrologic causality between multiple disturbances like insect infestation. Although we can speculate on the driving processes

behind the residual differences between physiographic characteristics, the empirical models do not elucidate mechanistic relationships behind post-fire hydrologic disturbance.

Moreover, multilinear models assume a linear relationship between the climatic predictor variables and streamflow. We must consider the effects of long-term rising temperatures on hydrologic recovery. Rising temperatures can alone affect the water balance of a watershed like increasing rates of transpiration, vapor pressure deficit, and snow sublimation. The linear regression models used in this study do not capture any higher-order, exponential relationships between streamflow and climate that could exist from increasing temperatures. In recent decades due to drought conditions, streamflow, especially low flows, has declined in many western watersheds (Dudley et al., 2020). This trend possibly masked some of the post-fire hydrologic effects on streamflow (Hallema, Sun, Bladon, et al., 2017). That said, this study did find that many watersheds showed increased low flows after large forest fires.

We only considered the percent burned area, yet this assumes a homogeneous burned effect across the portion of the basin burned. Studies show that high-severity forest fires and stand-replacing disturbances elicit a distinct hydrologic response compared to low-severity fires (Goeking & Tarboton, 2022; Williams et al., 2022). High burn severities can affect infiltration rates and soil susceptibility to surface sealing leading to more surface runoff that may exceed the influence of altered evapotranspiration on the water balance (Atchley et al., 2018; Ebel & Moody, 2017). Whereas patchy, low-severity forest fires can result in decreased streamflow due to elevated evapotranspiration rates due increase understory growth post-fire (Hallema, Sun,

Caldwell, et al., 2017). Moreover, the location of the burn in the watershed has profound impacts on the hydrologic response. In the last 20 years, the burned area in the seasonal snow zone has increased by 9% each year (Gleason et al., 2019). The impact of fires in the season snow zone is consequential. High to moderate-severity fires can lead to snow disappearance and reduced peak SWE, influencing the timing and magnitude of spring runoff (Kampf et al., 2022; Koshkin, 2022; Smoot & Gleason, 2021). In recent years, the Sierra Nevada has seen approximately 10 times more fires in the seasonal snow zone. Additional snow droughts in this area have amplified earlier snow disappearance in burned areas (Hatchett et al., 2023). We have yet to determine the threshold burn extent in the seasonal snow zone to observe impacted streamflow, not unlike the approximate estimate of 20% drainage area disturbed to observe hydrologic change (Hallema, Sun, Bladon, et al., 2017; Williams et al., 2022; Wine et al., 2018).

Inter-basin comparisons were limited by the location and data availability of USGS reference gages that had burned during the time period of 2000 - 2020 (Falcone, 2011). To elucidate multi-characteristic statistical relationships between watershed groups we would need a great sample of burned reference watersheds. For example, we are unable to directly understand how the aridity of snow-dominated watersheds impacts the post-fire residuals comparing snow-dominated watersheds where $PET/P > 1$ and snow-dominated where $PET/P < 1$.

2.6 Conclusions

We analyzed climate, forest fire, and streamflow data in 95 watersheds across the western U.S. to investigate whether there was a change in high and low streamflow after

a forest fire. Our study focused on sub-monthly streamflow metrics and built upon existing research on hydrologic disturbance, which has mostly focused on annual water yield. Through multilinear analysis, we were able to quantify the change in 7-day summer low flow, 7-day spring peak flow, and the day of freshet in relation to the expected amount based on climate drivers such as P, T, PET, and SPEI after a fire. Results show summer low flows showed increases in streamflow for at least five years after a fire. Moreover, in snow-dominated watersheds, spring peak flows increased in magnitude and the day of freshet shifted to earlier in the years. Summer low flow positively scaled with the percentage of the watershed burned. This trend was exaggerated in snow-dominated watersheds. This work signals the importance of considering the effect of forest fires on the future water supply of the western U.S. Importantly, the how variability in watershed response will affect future water-risk.

CHAPTER 3. CONCLUSION AND IMPLICATIONS FOR FUTURE WORK

Wildfires are progressively impacting more to western U.S. watersheds, increasing in size, frequency, and severity in recent decades. Many of the major U.S. river basins including the Columbia, Colorado, Great Basin, and the American have experienced an increase in wildfire frequency since 2000 (Williams et al., 2022). Many of the urban centers in the western U.S. rely on mountainous, forested watersheds for their water supply. Globally, naturally high-quality drinking water from montane forests is a multi-billion-dollar economy where water managers and many miles of infrastructure rely on annual predictability. Forest fires pose an uncertain problem for the western U.S. water supply altering many key watershed processes. The change in evapotranspiration, infiltration, interception, and other interacting hydrologic pathways creates variability in the annual hydrograph. In this work, I aim to understand how wildfires alter the asymmetry of the hydrograph, low flows, and peak flows. We sought to ask if summer low flows, spring peak flows, and spring onset timing change after a forest fire. Additionally, if subregional and climatic watershed differences elicited distinctive hydrologic responses.

Chapter 2 of this thesis approached these questions through the time-trend analysis across 95 burned watersheds in the western U.S. (Zhao et al., 2010b). Using empirical models for each watershed, we calculated the expected streamflow based on climate factors. After the fire, the residual difference between the climate-based expected streamflow and the observed streamflow can be attributed to the effects of the forest fire. We looked at model residual patterns in all burned basins for each hydrologic metric to

determine the regional trend for summer and spring streamflow across the western United States.

We found that summer low flows and spring peak flows would likely increase after a forest fire across the western U.S. Summer low flows increased by 0.29σ and spring peak flows increased by 0.19σ . Additionally, we found that the freshet will likely occur earlier in snow-dominated watersheds that have burned. On average the day of freshet will occur one week earlier than expected from climate variation.

Additionally, we found the percent watershed burned to be positively correlated with larger streamflow residuals for summer low flows and spring peak flows, suggesting that greater burned area results in great streamflow change. This finding advances the wealth of studies that find that larger disturbances contribute to increases in annual streamflow (Hallema et al., 2018; Saxe et al., 2018; Williams et al., 2022). However, we found that the timing of the freshet did not have a strong correlation with the percent of the basin burned, suggesting other burn processes affect the timing of streamflow. Importantly, this work signals the importance of disaggregation watersheds based on key physio-climatic relationships. We found less arid basins have a larger post-fire summer low flow response with a five-year mean residual of 0.44σ . In agreement with dissenting disturbance studies, we found more arid basins show no significant low flow response (Biederman et al., 2022; Goeking & Tarboton, 2022). Further, low flows in snow-dominated watersheds were more sensitive to increases in the percentage of the watershed burned. The reduction of canopy interception in snow-dominated watersheds could have a larger impact on the amount of accumulated precipitation than in rain-dominated watersheds.

In addition to the long-term aridity, post-fire response in annual streamflow and base flow recession can vary between wet and dry years (Biederman et al., 2022; Kinoshita & Hogue, 2015a). Further work could be done to understand how interannual meteorological variability could affect high and low flows of the hydrograph, and if these climate patterns could have masked or exacerbated our residual findings. Biederman et al. (2022) separated wet and dry years in their analysis because dry years did not scale with precipitation. Additional work could be done to understand how different streamflow metrics for high and low flows respond to wildfire. In Chapter 2, we only focused on three metrics, 7-day low flow 7-day peak flow, and day of freshet, yet there are there many other measurements to quantify duration, frequency, variability, and severity of high and low flows (Eng et al., 2017). However, an important future step of this work is to compare these nationwide empirical models to a physically based model. Although this work aims to understand correlated large-scale changes, physically based models would all use to understand the driving processing behind the post-fire hydrologic responses (Atchley et al., 2018; Boisramé et al., 2019; Maina & Siirila-Woodburn, 2020). Process-based models would allow for more specific watershed management recommendations, especially when modeled at a watershed scale or smaller.

This work would not be possible without the maintenance of long-term streamflow gages in watersheds with minimal management. We stress the importance of reference streamflow gages to understand the effects of forest fires in a nonstationary climate. The homogenization of data collection and streamlined data availability would allow for cross-network comparison. Our study was limited by the location and data availability of USGS reference gages (Falcone, 2011), however, the incorporation of

other stream gauge networks could allow for a more representative study for all regions of the western U.S.

As we continue to understand the implications of forest fires on water resources across the western U.S., we must reckon with the regional and subregional variability of watershed response. This work highlights that is not a single water management solution, but multiple ways to best adapt to western-wide forest fires. Future and current forest fires have a tremendous impact on local and regional water resources. Although post-fire increases in peak and low flow could be perceived as a benefit to water resources, these influxes are not always an economic advantage. After the 2002 Hayman fire, Denver Water spent \$30 million dollars dredging runoff sediment in their reservoirs (Bladon et al., 2014). Increased peak flows could cause increased transportation of instream sediment or debris flows elevating risks to water infrastructure (Coombs & Melack, 2013; Helvey, 1980). The nonstationary of water resources further confounds post-fire hydrologic response (Milly et al., 2008). Low-to-no snow years and increasing climate extremes have profound impacts on low and peak flows (Corringham et al., 2022; Hammond et al., 2023; Siirila-Woodburn et al., 2021). Increasing forest fires add uncertainty and variability to future streamflow projections. In the arid Southwest, watersheds are projected to experience severe water scarcity (T. C. Brown et al., 2019), yet these regions likely to not experience an advantageous boost in post-fire low or peak flows. As the increased presence of large wildfires becomes our paradigm across the western U.S., we must incorporate the effects of fire into our future and current water supply projections.

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SUPPLEMENTAL MATERIAL

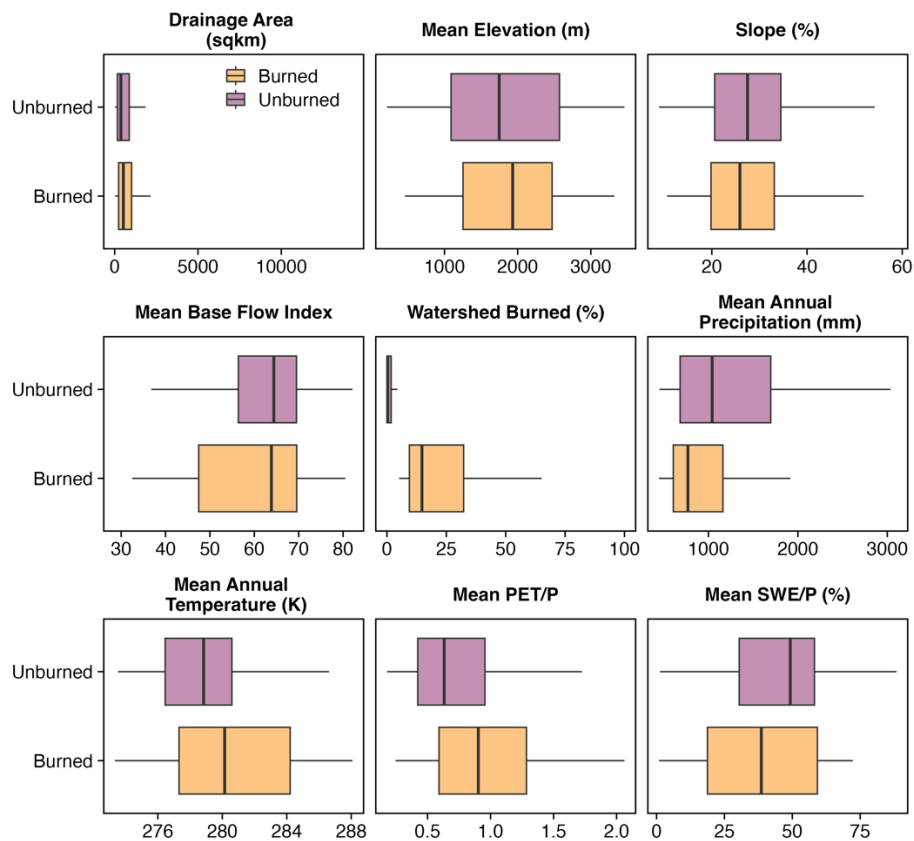


Figure S 1. Climatic and Physiographic characteristics for burned watersheds. Drainage area (km^2), mean elevation (m), slope (%), mean base flow index, mean SWE/P, and mean PET/P are derived from the USGS Gages II dataset (Falcone, 2011). The percent watershed burned was calculated from MTBS. Mean Annual precipitation (mm), and temperature (K) was calculated from the time period 1990 – 2020 using the GridMET dataset (Abatzoglou, 2013).

Andrews Creek WA, Snow-Dominated

Fire Year = 2003 : Percent burned = 96.1 : PET/P = 0.55

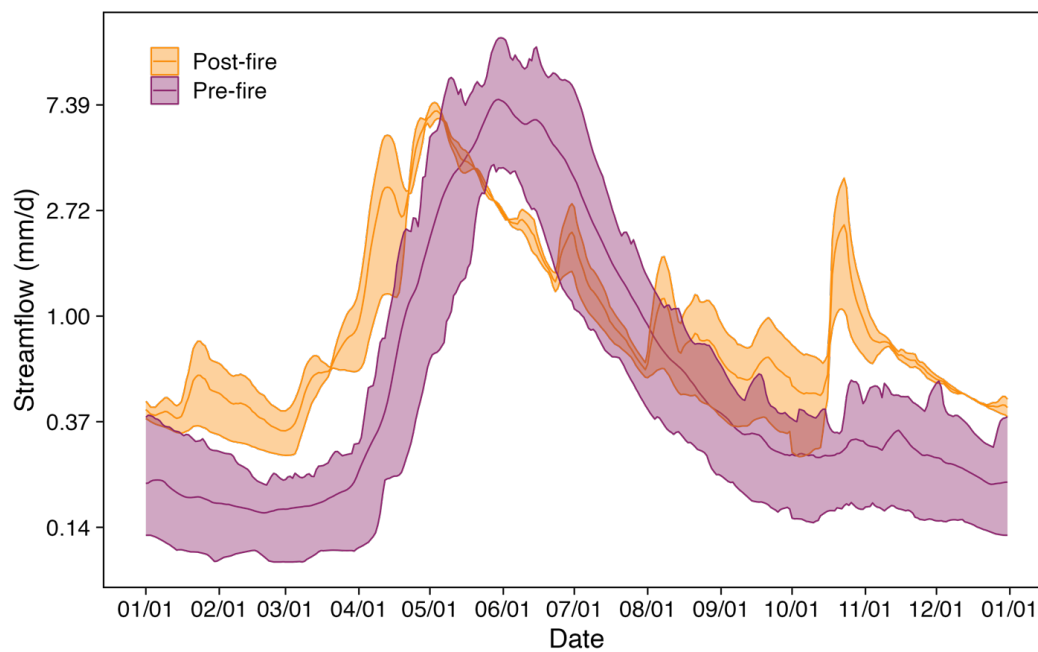


Figure S 2. The annual hydrograph for the Andrew's Creek watershed near Mazama, WA. The pre-fire annual hydrograph (purple) is compared with the post-fire annual hydrograph (orange). The solid line on each hydrograph shows the mean annual streamflow whereas the shaded areas show 80% of streamflow variability. This snow-dominated watershed burned in 2003 and is energy limited with $PET/P < 0.55$.

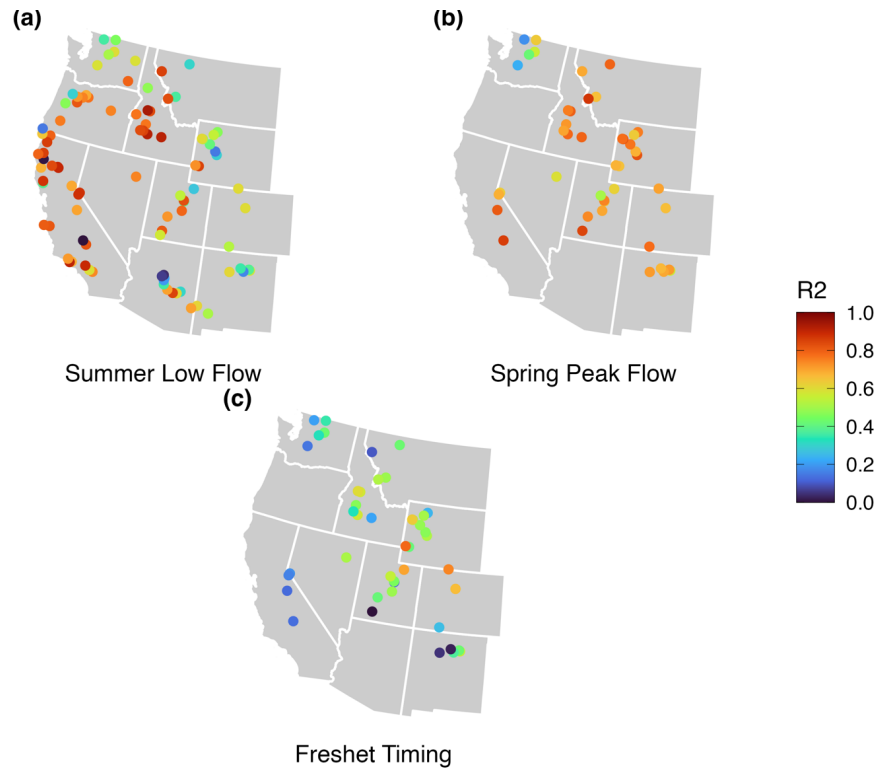


Figure S 3. Predictive model performance for streamflow metrics during pre-fire period for burned watersheds. Model selection used leave-one-out cross-validation for (a) Summer Low Flows, (b) Spring Peak Flows, and (c) Freshet Timing.

Table S 1. Model performance for each streamflow metric. NSE, R^2 , and RMSE represent the mean value across all burned modeled watersheds.

Streamflow Metric	NSE	R^2	RMSE
Summer Low Flow	0.60	0.61	0.59
Spring Peak Flow	0.68	0.68	0.54
Freshet Timing	0.37	0.39	0.77

Table S 2. *The number of watersheds with a net number of significant years where the streamflow metric residual is significant from 95% of the unburned streamflow metric residuals during the post-fire time period. We calculated the net number of significant years to understand the overall post-fire trend. For example, if a watershed had 3 years of significant positive residuals, and 1 year so significant negative residual, the net years of residuals would be positive 2 years. The number of watersheds for a set of years is the sum of the individual watershed's net residual years.*

Streamflow Metric	Watersheds with significant total negative residuals years		Watersheds with no total significant residual years	Watersheds with a significant total positive residuals years	
	≥3 years	1 – 2 years	No change	1 – 2 years	≥3 years
Summer Low Flows	0	14	64	13	5
Spring Peak Flows	0	4	36	4	0
Freshet Timing	1	5	36	1	1

Table S 3. *The post-fire years in which the burned streamflow metric residuals is significantly different from the unburned streamflow metric residuals (p -value < 0.05). A single year represents that year since the fire burned residual for each watershed compared with the same year for the unburned watersheds. For example, year 2 is significant for summer low flows if the summer low flow residuals for year 2 after a fire are different from the post-fire year 2 summer low residuals from randomly selected unburned watersheds. We calculate the cumulative year significance by calculating the running mean residual for each year following a fire. We excluded post-fire years with >10 burned watersheds because of the small sample size.*

Streamflow Metrics	Single Year Significance	Cumulative Years Significance
Summer Low Flows	1, 2, 3, 5	1 – 19
Spring Peak Flows	2, 3	2 – 15
Freshet Timing	2, 3, 6, 11	1 – 15

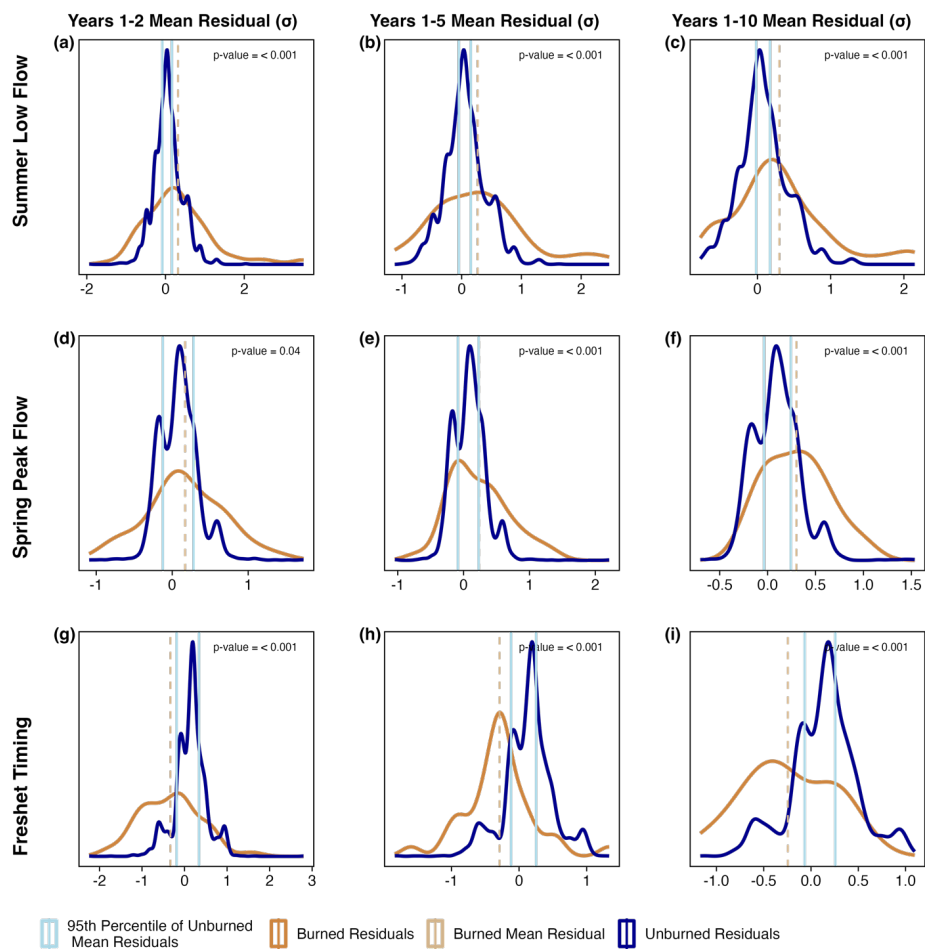


Figure S 4. The mean residuals for years 1-2, 1-5, and 1-10 for all burned and unburned watersheds across each metric, Summer Low Flow, Spring Peak Flow, and Freshet Timing. The residual means for each watershed are represented in brown (burned) and dark blue lines (unburned). The vertical dashed tan line is the mean multi-year residual across all burned watersheds. The two vertical light blue lines represent the 5th and 95th quartile of the mean multi-year residual for each unburned watershed simulation.

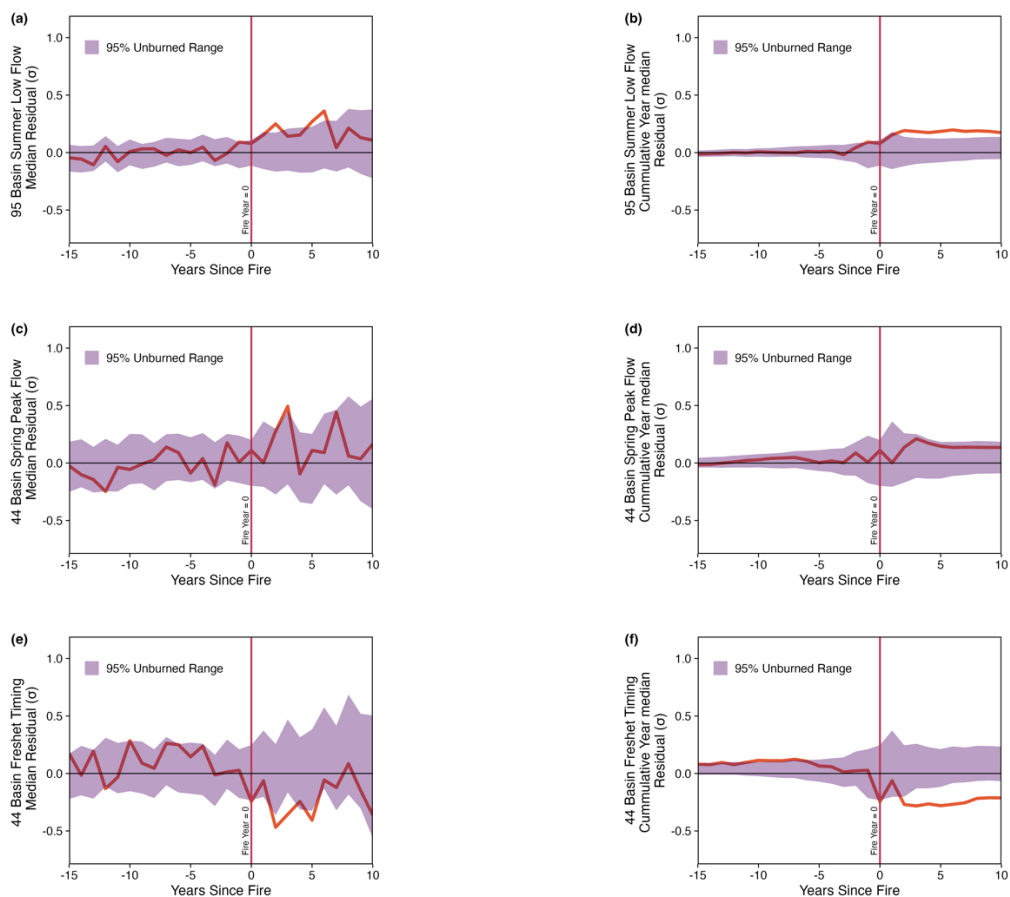


Figure S 5. The multi-year residual medians across burned basins in units of standard deviations. For example, the dark line at year 5 represents the mean residual change for years 1-5 across all burned basins. The shaded areas represent the 95th percentile of the unburned basins. For the calculated streamflow metrics from top-left to bottom-right: maximum 7-day flow, maximum 7-day flow during the months of April- July (AMJJ), the day of maximum 7-day flow, the day of maximum 7-day flow during AMJJ, the day of spring flow onset, the minimum 7-day flow during the months of June - September (JJAS), and the minimum 7-day flow during the months of June - October (JJASON).

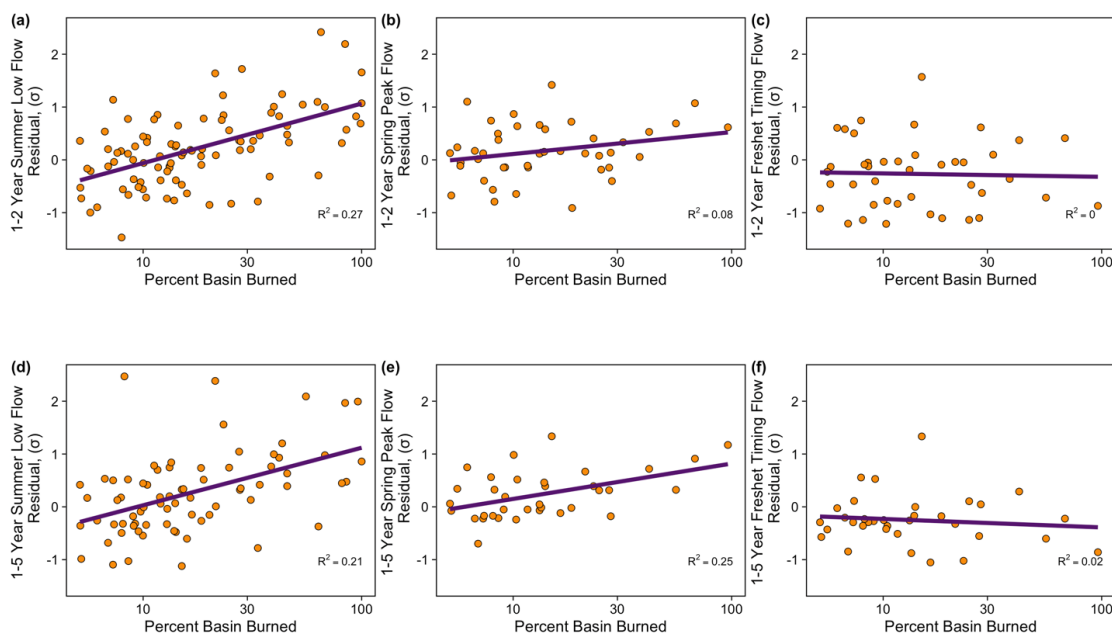


Figure S 6. The relationship with the percent of the watershed burned and each streamflow metric: summer low flow (a, d), spring peak flow (b, e), and timing of freshet (c, f). (a) – (c) show the 1-2 year mean residual, standard deviations (σ) and (d) – (f) show the 1-5 year mean residual. The orange points are the mean residual for each watershed and the purple line signifies the linear relationship between the percent watershed burned (log-scale).

Table S 4. Linear regression results of residual mean and percent basin burned.

Streamflow metrics	1-2 year residual mean			1-5 year residual mean		
	Slope	R ²	p-value	Slope	R ²	p-value
Summer Low Flow	0.018	0.27	>0.001	0.016	0.21	>0.001
Spring Peak Flow	0.0082	0.084	0.0057	0.012	0.25	0.0025
Freshet Timing	0.000018	>0.001	0.98	- 0.0036	0.0018	0.44

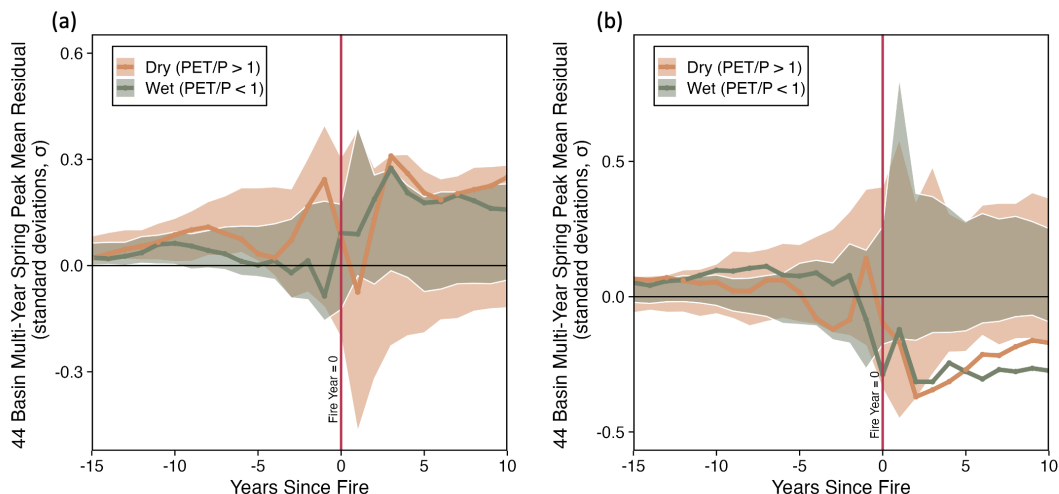


Figure S 7. Aridity does not appear to control spring peak flow and freshet timing post-fire response. Wetter, energy-limited watersheds where $PET/P < 1$ are shown in green and whereas drier, water-limited watersheds where $PET/P > 1$ are shown in brown. The vertical red line represents the fire year. The shaded area shows the 95% unburned range for both wet and dry watersheds.

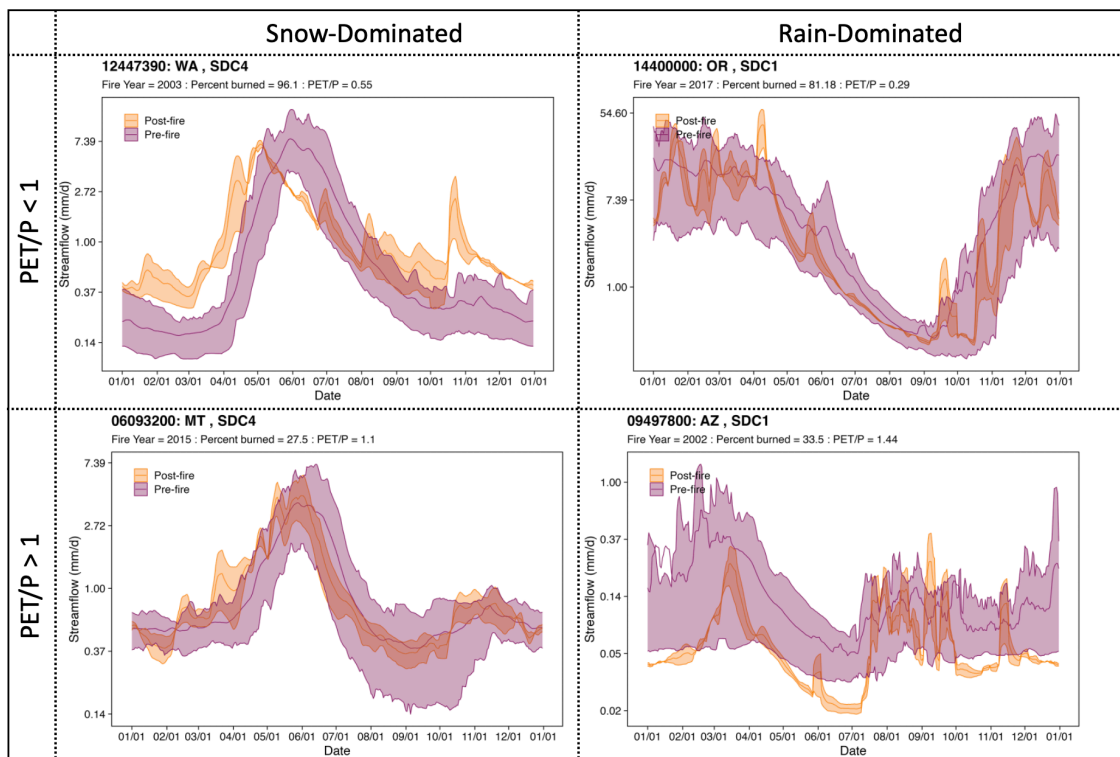


Figure S 8. The annual hydrographs for example watersheds that were burned $>20\%$. These watersheds are separated by aridity $PET/P > 1$ or $PET/P < 1$ and snow-dominated versus rain-dominated. The pre-fire annual hydrograph (purple) is compared with the

post-fire annual hydrograph (orange). The solid line on each hydrograph shows the mean annual streamflow whereas the shaded areas show 80% of streamflow variability.

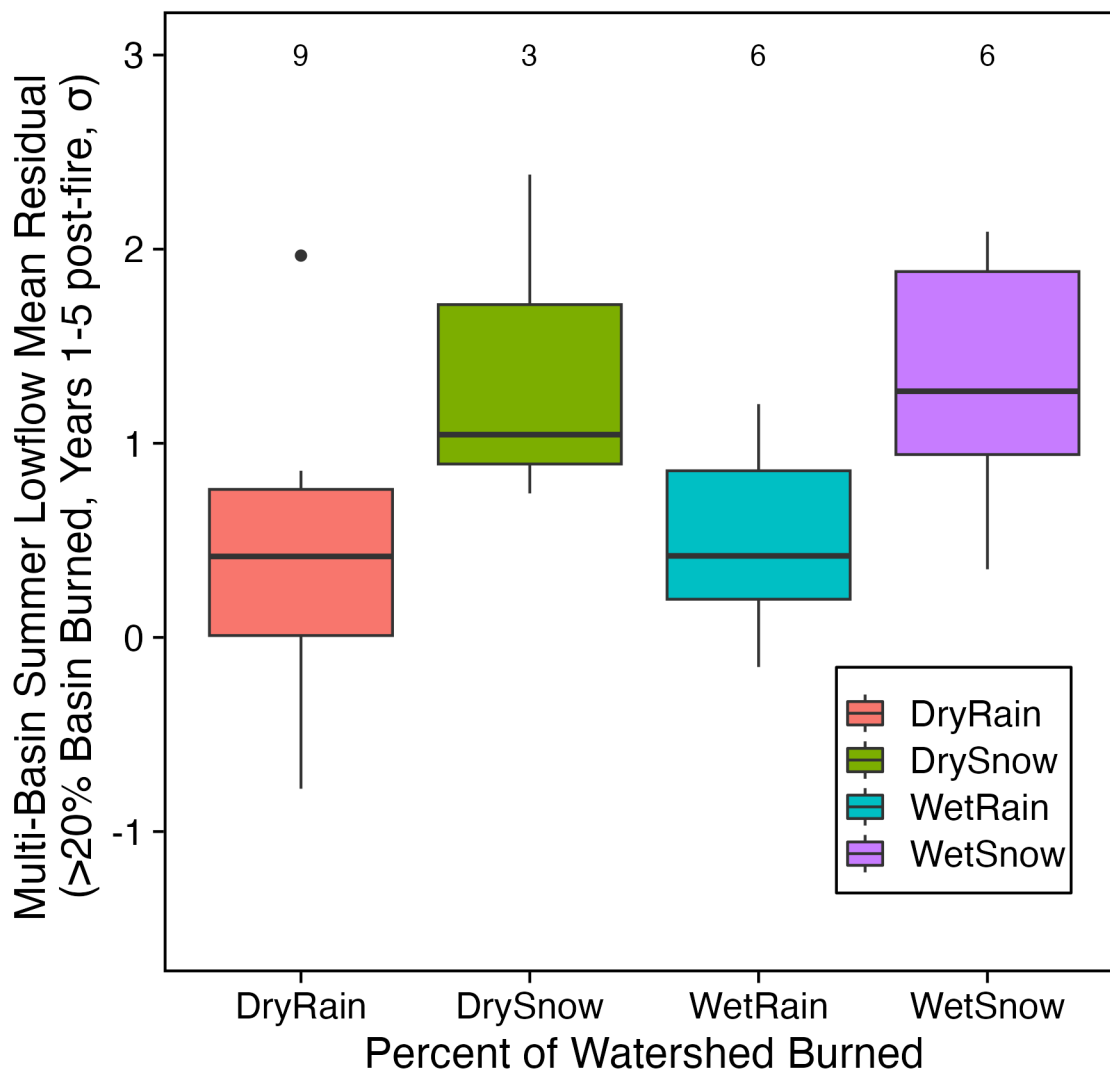


Figure S 9. The effect of the aridity and Snow melt contribution on summer low flow residuals. Boxplots of mean summer low flow residuals for years 1-5 based on burned watersheds that burned >20% of the drainage area. Watersheds are aggregated by snow-dominated or rain-dominated hydrographs (“Rain” and “Snow”) and PET/P > 1 or PET/P < 1 (“Dry” or “Wet”). The number of watersheds in each group is listed at the top of the plot.