MODELING POST-WILDFIRE MOUNTAIN HEADWATERS HYDROLOGY IN AN EXPERIMENTAL WATERSHED IN COLORADO

by

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ABSTRACT

The number of wildfires and the resulting total burned area has been increasing in Colorado. Besides disturbing vegetation, wildfires have both immediate and long-term effects on hydrologic and biogeochemical cycles of forested mountainous areas. Severe fires generally reduce water infiltration into the soil, increasing surface runoff and causing nutrients and sediments to wash away and subsequently compromise the quality of downstream water resources, in addition to creating landslide and flood hazards. After wildfires, agencies rapidly act to minimize nutrient loss and topsoil erosion using different slope-stabilization methods, such as wood-shred mulching. In these scenarios, hydrologic modeling is a useful tool to understand how perturbations to the water cycle may influence flows, but limited data is available in remote, rugged, burned landscapes for model inputs. This study applied the Agricultural Ecosystems Services (Ages) semi-distributed ecohydrology model using various gridded climatological datasets to simulate post-fire hydrological responses at sites affected by the Cameron Peak wildfire in Colorado.

The study provides insights into vegetation and hydrology interactions across various watershed locations, influenced by factors like crop type, elevation, and aspect. Notably, unburned HRUs displayed consistent interception of precipitation throughout the growing season, contrasting with burned HRUs, which showed increasing interception capability as they revegetated. This difference underpins the significant hydrologic alterations post-fire, with burned areas experiencing higher throughfall and less water retention, leading to increased surface runoff, especially following significant precipitation events. This study focuses on both hourly and sub-hourly resolutions for capturing detailed process dynamics, as well as finer spatial resolution than many hydrologic models, which are not common and represent important first steps toward simulating post-fire hydrologic responses at the appropriate spatiotemporal scale.

Calibration metrics, including the Kling-Gupta Efficiency (KGE), Nash-Sutcliffe Efficiency (NSE), and percent bias (PBIAS) highlighted the model's competent representation of general hydrologic conditions (KGE = 0.7-0.76; NSE =0.12-0.47). However, discrepancies in peak flow predictions emphasized the need for model adjustments, particularly in accurately capturing large runoff events. This aspect was critical during the calibration period, where the model struggled with prediction of peak flows in the calibration period (PBIAS = 36%), but improved significantly for the validation period (PBIAS = 1%).

The model's ability to operate at sub-hourly resolutions opens new avenues for detailing the timing of runoff events, a crucial feature for managing flood risks and monitoring watershed health in post-fire scenarios. This level of temporal resolution is particularly beneficial for capturing the rapid hydrological

responses characteristic of smaller or steeply sloped subwatersheds. In this regard, the Bennett Creek Ages model has the advantage over most post-fire modeling studies as the temporal scale is more appropriate for simulating post-fire hydrologic responses. Modeled time of concentration is slightly elevated for mulched subwatershed than unmulched subwatersheds.

This research contributes to advancing knowledge in the areas of mountain and fire-related hydrologic modeling, high-resolution modeling using remote-sensing data, and informs agencies of the impacts of best management practices in critical zone rehabilitation treatments after wildfires.

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CHAPTER 1 INTRODUCTION

1.1 Literature Review

1.1.1 Prevalence of Wildfire in Colorado

The American West experienced a significant increase in large wildfire occurrence, wildfire duration, wildfire size, and length of fire seasons starting in the mid-80s (Higuera et a., 2021; Kampf et al., 2022; Westerling et al., 2006). Forests in the Colorado Front Range used to experience more frequent low and moderate intensity fires than in recent times (Addington et al., 2018), and contemporary fires are becoming more severe (Dillon et al., 2011; Sherriff et al. 2014). This trend is most pronounced in the Northern Rocky Mountain mid-elevation forests. Fire risk in the Rocky mountains is more influenced by climate than land use history, where earlier spring snowmelt and increased spring/summer temperatures coincide with increased wildfire metrics (Westerling et al., 2006). Westerling et al. found that 66% of variance in annual fire incidence is attributed to spring and summer temperatures. Average fire season length increased by 64% (78 days) between the 1970-1986 and the 1987-2003 periods. Comparing these same periods, the average time to control wildfires increased from 7.5 to 37.1 days. Out of the total increase in wildfire frequency in the Western US, 60% has been in the Northern Rocky Mountains. (Westerling et al., 2006). The 2020 fire season saw nearly double the total area burned since 1984 in the Central Rocky Mountain subalpine region (with 44% of burns in 2020 alone). Based on paleo fire records, 21st century fire rotation period has nearly doubled compared to the past 2,000 years (=117yrs). This rate is 22% higher than any period in the past 2,000 years. (Higuera et al., 2021)

Climate change is expected to cause wildfire frequency to increase (Littel et al., 2009; Liu et al., 2015; Moritz et al, 2010; Westerling et al., 2006). Forests in the Colorado Front Range used to experience more frequent low and moderate intensity fires than in recent times (Addington et al., 2018), and contemporary fires are becoming more severe (Sherriff et al. 2014; Dillon et al., 2011). During the year of a fire, mountainous areas generally have little precipitation, drought conditions, and higher than average temperatures. This suggests that the main climate driver of wildfires is the drying of fuels and increased fuel production, termed “climatic preconditioning” (Littel et al., 2009). Using a large collection of post-fire tree revegetation data from the Rocky Mountains, researchers found that postfire tree seedling establishment decreases in warm, dry conditions, and that with observed and projected climate change trends, trees will not able to reestablish themselves as easily as in the cooler, wetter past climate (Rodman et al., 2020). Up to 39% of the variability in wildfire area burned in the Western US from 1916-2003 is attributable to climate variables (Littel et al., 2009). From 2001 to 2020, the average latitude of fires in Colorado has increased, with an active fire hotspot in the central northern part of the state (which includes the Cameron Peak Fire). (Wright and Roy, 2022) In chapparal ecosystems, locations and spread of large wildfires is determined by extreme wind events (Moritz et al., 2010). High wind conditions in recent fires in Colorado may suggest that this is also true of forested mountain and grassland ecosystems. A meta analysis of many thousands of wildfires found that the most destructive fires were those with very high growth rates (including the Cameron Peak fire and Marshall Fire), often exacerbated by high winds (Balch et al, 2024). There is also a clear trend that these high growth rates have been increasing over time. Climate change is expected to exacerbate the prevalence of these conditions.

1.1.2 Wildfire-Related Hydrologic Processes

Wildfires are known to affect the hydrologic cycle via loss of vegetation, physical and chemical soil properties, and changes to physical landscape properties, with varying severity (Doerr et al., 2006; Ebel, 2022; Garcia-Chevesich 2015; Wieting et al., 2017). Loss of vegetation usually equates to a loss of interception storage, which allows more sedimentation to occur from direct rainfall onto land surfaces (DeBano, 2000; Garcia-Chevesich, 2015; Lavabre et al., 1993; Scott, 1993). Evapotranspiration rates can also be impacted substantially after wildfire, but whether it increases or decreases is highly variable based on fire severity, biome, and other landscape attributes (Collar et al., 2021). After four wildfires in subalpine regions of Colorado and New Mexico, evapotranspiration decreased and was correlated with burn severity (Mankin and Patel, 2023). In the region of the Rocky Mountains known as the “late snow zone”, areas affected by wildfire experience lower magnitude peak snow accumulation and snow-free dates 2-3 weeks sooner than unburned areas; both regionally and in the Cameron Peak burn scar. (Kampf et al., 2022; McGrath et al., 2023)

Fire can consume and alter the organic layers in soil, causing compaction. Combusted organic matter often forms a hydrophilic layer of ash at the surface of the soil which can absorb and store some amount of precipitation, but eventually washes away (Cerdà and Doerr, 2008, Ebel et al., 2012; León et al., 2013; Moody et al., 2009, Nyman et al., 2014). Below the ash, a crusty layer of burnt soil layer often forms, though is spatially variable and related to fire severity and the amount and composition of organic material pre fire (DeBano, 2000; Garcia-Chevesich et al., 2010). This crust is made of organic material bonded to sediments and exhibits a hydrophobicity that significantly impedes infiltration, reduces hydraulic conductivity and water retention, and increases soil-water repellency for months to years following a fire (Bodí et al., 2012; Doerr et al., 2006; Ebel et al., 2012; Ebel, 2022; Ebel and Martin, 2017; Garcia-Chevesich et al., 2010; Garcia-Chevesich, 2015; Moody et al., 2009; Robichaud, 2000; Wilkinson et al., 2009). Soil water repellency has also been associated with soil burn severity (DeBano 2000). Moody and Ebel (2012) found that the ash layer present after the Fourmile Canyon Fire in 2010 was hydrophilic and able to absorb up to 0.6mm rain per 1mm ash thickness and can play a significant role in controlling runoff generation (Ebel et al., 2012; Ebel and Moody, 2017; Moody and Ebel, 2012). Studies in Spain and Colorado have both found that the amount of ash present is very well correlated with reduction and delay of surface runoff, but storms with enough rainfall to overwhelm this storage produce surface runoff since the hydrophobic layer below reduce infiltration rates significantly, and under certain conditions, nearly to zero (Bodí et al., 2012, Ebel et al., 2012, Martin and Moody, 2001). Other researchers in Colorado found that following controlled experimental burns at the Boulder Creek Critical Zone Observatory that soil organic matter is reduced proportionally with the temperature of a fire, but that while infiltration was reduced at low to moderate temperature burns, but high temperature burns could result in the loss of all organic matter and increases in infiltration rates (Wieting et al., 2017).

These alterations, especially more severe ones, can contribute to elevated post-fire peak flows (Beyene et al., 2021; Robichaud, 2000), water yield (Campbell et al., 1977; Hasan et al., 2020; Kinoshita and Hogue, 2011; Kinoshita and Hogue, 2015), faster/flashier runoff event timing and increased risk for large flood and landslide events (Garcia-Chevesich, 2015; Robichaud et al., 2016) and soil erosion, which has been found to further degrade water quality and increase sediment transport to downstream water bodies for years following fire (DeBano, 1991; Ebel, 2020) in the Colorado Front Range (Murphy et al., 2015). Additionally, changes to the organic layer and loss of topsoil cause nutrients to wash away and runoff to tributary streams, compromising the quality of downstream water (Coalition for the Poudre River Watershed, 2022b; DeBano, 1991; Garcia-Chevesich, 2015; Rhoades et al., 2019a; Rhoades et al., 2019b). Not all wildfires cause increased runoff, however. Individual studies (Doerr et al., 2006; Hallema et al., 2017, Saxe et al., 2018) and reviews of studies (Moody et al., 2013) have shown variable and/or decreasing of runoff volumes, peak flow rates, and erosion rates following fires which have been attributed to variable geomorphology and vegetation, complex climate patterns, higher sensitivity to variation in climate than effects of fire, and the idea that perhaps runoff responses to wildfire are more nuanced or have additional confounding factors.

1.1.3 Post-Fire Treatments

To mitigate these risks and promote healthy regeneration of topsoil and plant populations, land managers sometimes apply shredded wood mulch in key burned areas where fire-altered hydrology is suspected to cause excess surface runoff or sedimentation (Bombino et al, 2020; Robichaud et al., 2010; Robichaud et al., 2013a; 2013b; 2013c; 2013d). In a study of wood shred mulch effectiveness as a post-fire treatment, it was concluded that mulching slowed surface runoff velocity and helped pond and infiltrate a greater proportion of surface runoff to the degree that it was equivalent to accelerating the land 1 year into recovery (Robichaud, 2013a). Another study of mulch effectiveness in the Colorado Front

Range found that mulching, and to a lesser degree, contour-felled log barriers, were very effective at reducing sedimentation post fire, while seeding had no measurable effect (Wagenbrenner et al., 2006). Wood mulch following wildfire in the Rocky Mountains was found to increase the density of plant seedlings and soil moisture following the High Park Fire (Jonas et al., 2019). In cases where vehicle access is limited, mulch may be applied aerially from helicopters. Descriptions of this process can be found in Robichaud et al., 2013b. In other cases following fires in Colorado, such as the Cameron Peak fire, where mulch was aerially applied from helicopters in an experimental treatment area found no measurable effect on sediment yields (Geller, 2023). Other mitigation treatments include but are not limited to: placing erosion barriers such as contour-felled logs, trenches, sediment fences, and check dams; manual soil tillage or preparation, and seeding (Garcia-Chevesich, 2015; Robichaud et al., 2010; Zema 2021). Previous studies have estimated the effectiveness of such mitigation treatments using modeling tools (Lopes et al., 2020; Robichaud et al., 2007; Rulli et al., 2013; Schmeer et al., 2018; Vieira et al., 2018; Zema et al., 2020a; Zema et al., 2020b; Zema, 2021). It has been noted that most of these post-fire treatments have a greater impact on erosion control than hydrologic regimes (Robichaud et al., 2013d; Zema, 2021).

The United States Forest Service (USFS) Rocky Mountain Research Station in Ft. Collins conducts research in Colorado’s forests and has studied the impacts of wildfires in the region, along with members of Colorado State University’s (CSU) faculty and staff at the United States Department of Agriculture (USDA) Agricultural Research Service (ARS), both also located in Ft. Collins. Their investigations span hydrology, soil science, ecology, and forestry, among others. They also investigate the efficacy of the treatment strategies that are applied to watersheds after wildfires, including mulch. Though mulching effects are not a central focus of this study, it is a part of their efforts to study the hydrology of a site where mulch was applied following a fire.

1.1.4 Post-Fire Hydrologic Modeling

Water and land managers routinely employ various types of hydrologic models to assist in flood forecasting and planning for potential challenges within their respective management domains. Empirically-based, or data-driven models, use statistical or machine-learning methods to leverage empirical relationships that have been established through previous studies to produce relationships between system inputs and outputs. Some popular applications of empirical models in post wildfire conditions include statistical regressions and runoff curve numbers. Some empirical models have been developed specifically for application in wildfire-effected areas, such as the Rowe, Countryman, and Storey (RCS) model, which uses empirical relationships from historical fires to estimate peak flows (Rowe et al., 1949). It has been demonstrated that this method does not perform very well across all settings, perhaps due to the data the model is based on being outdated and specific to Southern California (Kinoshita et al., 2014; Wilder et al., 2020). Curve Number methods employ established empirical relationships involving land cover, soils, and rainfall to estimate rainfall-runoff generation relationships (U.S. Department of Agriculture, Soil Conservation Service, 1991). These methods can be used to estimate peak flows and runoff event timing. Curve number approaches have been developed specifically for post-wildfire settings, accounting for factors such as time after fire, spatial connectivity of burned areas, and burn severity, and can estimate peak flows and runoff generation thresholds (Moody 2012). In a study comparing five different hydrologic models to post-fire settings across the Western US, the RCS model, a linear regression equation published by the United States Geological Survey, and three curve number-based models were explored. The three models that use a curve number approach to estimate runoff generation were USDA Windows Technical Release 55 (TR-55) (U.S. Department of Agriculture, Natural Resources Conservation Service, 2009), Wildcat5 (Hawkins and Munoz, 2011), and HEC-HMS ((U.S. Army Corps of Engineers, 2010) (Kinoshita et al., 2014). TR-55 is typically used in small agricultural watersheds, while Wildcat5 was developed for and mostly used instep, mountainous catchments. The study found that in general, the curve number approaches performed better than the other empirical models for the estimation of peak flows and had less variable results (Kinoshita et al., 2014). Multiple have found that properly calibrated curve number based modeling approaches can produce accurate peak discharge estimates, which includes, in addition to previously mentioned models, KINEROS2 (Chen et al., 2013; Kinoshita et al., 2014; Lucas-Borja et al., 2020; Partington et al., 2021; Sidman et al., 2016). KINEROS2 (Goodrich et al., 2005) is a curve number based model, but also is a physically-based model because it represents some processes distinctly. It was applied in a post-fire setting in Utah and New Mexico and the study found that rainfall patterns and distribution play a significant role in runoff production and peak flows (Sidman et al., 2016). A comparison study between KINEROS2 and HEC-HMS models representing a wildfire in the San Dimas Experimental Forest found that HEC-HMS performed better in pre-fire conditions, while KINEROS2 performed better than HEC-HMS in post-fire conditions (Chen et al., 2013).

The HEC-HMS (U.S. Army Corps of Engineers, 2010) model has been used for flood forecasting, watershed analysis, water quality studies, and more, across many landscapes. It can be configured as a lumped, semi-distributed, or fully distributed mode, and has been found to perform better in post-fire applications in a distributed configuration (Kinoshita et al., 2014). HEC-HMS was applied to a burned catchment in California using a curve number approach, and was able to reasonably estimate storm volumes, peak flows, lag times, and peak flow timing using manual parameter adjustments (Cydzik and Hogue, 2009). It has also been applied in wildfire settings to predict peak flows and debris flow initiation with new tools that have been developed for use the HEC-HMS to model debris flows in addition to hydrology in post-fire settings. These tools employ empirical relationships involving proportion of area burned, time since fire, and antecedent moisture conditions (Pak et al., 2023).

In contrast, physically based models rely on an abundance of observational data to simulate hydrologic fluxes using process-based algorithms. These algorithms describe the individual hydrologic processes that are obscured and implicitly accounted for in empirical models. Some simple physically-based models have been developed specifically for predicting runoff and erosion in burned landscapes. These include but are not limited to: Fire Enhanced Runoff and Gully Erosion (FERGI) model (Luce, 2001) and Water Erosion Prediction Project (WEPP) model (Flanagan et al., 1995). FERGI is able to model treatment strategies such as log erosion barriers, while WEPP has streamlined functionality for spatial data inputs and predicts runoff and erosion using representations of burn severity and adjustments to soil hydraulic properties. The MIKE SHE model (Graham and Butts, 2005) is a distributed, physically-based model that is very widely used in Europe. It was applied to a burned area in California and represented wildfire using changes to land cover representation. The study demonstrated that increases to streamflow were roughly proportional to the size of the fire (McMichael and Hope, 2007).

For flood forecasting and investigations of hydrological processes, the SWAT model (Arnold 1998) is widely used to characterize and quantify the effects of land-use change and mitigation on nutrient cycling, runoff, infiltration, and other hydrological responses, showing very good results in various non-wildfire applications, from urban to agricultural to mountainous regions in Colorado (Lemonds and McCray, 2007; Tasdighi, 2017; Wei, 2018). SWAT is normally configured as a daily model, but is also sometimes applied in an hourly format. A subhourly version of SWAT was created for use specifically in urban watersheds, but is not routinely used (Shannak, 2017). Module tools have been introduced to simulate land use changes in SWAT, but not wildfire explicitly (Pai 2011). SWAT has successfully been applied to modeling flooding in flash-flood prone regions of Thailand, where it was used to model expected peak flows under different land use scenarios (Suwannachai et al., 2024), and in France, where it was used at an hourly time step to estimate flash flood discharge following intense rain (Boithas et al., 2017). SWAT has been applied in post-wildfire modeling in a daily configuration with successful results with adjustments to represent changes from the effects of fire (as most physically-based models represent wildfire); usually focusing on adaptation of hydrology, soil, and land cover parameterization based on burn severity, combined with calibration to observed data (Basso et al., 2020; Escobar et al., 2017; Havel et al., 2018; Meshesha et al., 2024; Morrison, 2015; Wampler et al., 2023).

The Precipitation-Runoff Modeling System (PRMS) (Markstrom et al., 2015) is another distributed, physically-based watershed model that has had limited application in post wildfire settings. It operates on a robust set of physical process-oriented algorithms whose parameterization can be separately adjusted for burned areas, though it has not been developed specifically for wildfire. PRMS is able to represent subsurface processes, but runs on a daily time step, which makes it ill-suited for modeling small catchments. It was applied successfully across multiple wildfire effected watersheds where its calibrated parameterization was used to help detect changes to hydrologic processes due to fire (Douglas-Mankin and Moeser, 2019; Logan, 2016; Moser and Douglas-Mankin, 2021). In another case, it was applied in comparison to the AgroEcosystem (Ages) model (discussed below). Both models were able to accurately predict increases in runoff responses following wildfire in subalpine Rocky Mountains, with Ages slightly outperforming PRMS (Mankin et al., 2022).

The Regional Hydro-Ecologic Simulation System (RHESSys) is a physically-based, fully distributed hydrology. nutrient cycling, and vegetation dynamics model that has been developed in an open-source fashion by researchers across a number of American Universities (Tague & Band, 2004). It has been applied in a number of post-wildfire settings that did not explore the implications of fire on runoff, often paired with a fire spread model called WMFire (Bart et al., 2020; Burke et al., 2021; Hanan et al., 2021; Kennedy et al., 2017). These studies mostly focused on vegetation dynamics and evapotranspiration. By making adjustments to the vegetation parameters in the model, but not making any changes to soil properties, a study in California was able to accurately predict stream flows in a burned catchment (Boisramé et al., 2019). RHESSys also has the advantage of representing subsurface processes, which some other process-based models, such as InHM (VanderKwaak, 1999) and ParFlow (Kollet & Maxwell, 2006) that have been applied in post-fire settings also share (Ebel et al., 2016; Maina and Siirila-Woodburn, 2020).

Recent advancements have also been made in the area of fully distributed, physically-based models that explicitly represent fire effects in hydrologic calculations. The PFHydro model (Wang et al., 2020) has been developed to automatically apply changes to vegetation interception and soil-water repellency based on burn severity. In the initial application of this model, it was compared to UFORE-Hydro (Wang et al., 2005), which is the model it was based on before wildfire-specific modules were added. Application of these two models to a burned watershed in California found that PFHydro had significant performance improvements over UFORE-Hydro (Wang et al., 2020). Li et al. (2023) also developed a new module for a hydrologic model, the Advanced Terrestrial Simulator (ATS), to explicitly account for soil water repellency in burned areas.

The Ages model (Green et al. 2015) is similar to SWAT, except routing of surface flow, interflow, and groundwater flow are distributed – runoff, interflow, and groundwater flow are allowed to flow laterally between Hydrologic Response Units (HRUs) and stream reaches rather than all automatically running into stream reaches. HRUs are areas that share characteristics where a modeler would expect a similar hydrologic response. The various hydrologic processes represented in a model (infiltration, percolation, surface flow, etc) are calculated per time step within each HRU and are routed to the next downstream HRU or stream reach. Most models, such as SWAT, lump processes within sub-watersheds, and many models only allow a HRU's flow to be routed to a stream channel, rather than another HRU. This distributed approach is a potential strength in post-wildfire hydrologic modeling, as patches of unburnt areas have been found to reduce hydrologic conductivity from burnt areas upslope of them (Cawson et al., 2013). Similar to RHESSys, Ages simulates vegetation processes as a part of the hydrologic cycle.

Sub-daily time steps are considered important for post-fire analysis because burns are typically within small portions of sub watersheds, and even small, hourly precipitation events can cause significant runoff within the flashy regime of post-fire hydrology. For post-fire modeling on a small watershed to hillslope scale, finer time and space discretization is thought to be important to capture processes at the level they occur (Li et al., 2023; Tarek et al., 2020; Wells et al., 2024). In a review of post-fire modeling studies, many found that peak discharges are most correlated with rainfall intensities at a 30-minute timestep or less, and that estimations of hydrologic processes such as lag time may be obscured. It was also highlighted in this review that it is an open question in post wildfire modeling research as to what time interval is best to use for accurate process representation, especially at varying spatial scales (Moody et al., 2013). Additional studies have indicated that it is necessary to use hourly or smaller timesteps when modeling the hydrologic effects of wildfire in the period immediately following fire (Partington et al., 2021; Partridge et al., 2024).

AgES has been shown to produce results comparable or superior to SWAT in a study of mixed agricultural and urban (unburned) watershed in Colorado (Veettil et al., 2021) and recently has been successfully applied to pre- and post-fire conditions in arid and subalpine environments in Colorado, New Mexico, and California in daily configurations (Mankin et al., 2022; Wells et al., 2024). In one of these studies (Mankin et al., 2022), parameters were calculated separately for pre- and post-fire model time periods. This study found that there were a number of parameters that had diverging values pre and post-fire, related to interception, evapotranspiration, and soil water processes. This separate parameterization allowed the model to perform well for both the calibration and validation periods, but allowed the authors to make inferences about fire-induced changes to hydrologic processes (Mankin et al., 2022). Due to the close working relationship between the USFS Rocky Mountain Research Station and the ARS, in addition to the advantages and abilities of Ages stated above, Ages was selected to construct a model for this study. As detailed in Chapter 2 – Methods, this study builds off the success of Mankin et al. (2022) in utilizing separate elements of burned and unburned calibration to understand the effects of wildfire on hydrology.

1.1.5 Data Limitations and Gridded Climate Datasets

In a study comparing four gridded meteorological datasets of varying resolution in a mountainous region of France, it was determined that the higher-resolution data produced a better performing model, which the authors attribute to better representations of weather variability in complex topography (similar to mountainous regions of Colorado) and the fact that it is common to observe rain events on a small spatial and temporal scale in the mountains (Raimonet et al., 2017). It is also difficult to obtain direct climate and streamflow measurements in burned catchments, since the inherent difficulties associated with instrument installation and maintenance are compounded by damages and field safety concerns caused by wildfire (Shakesby and Doerr, 2006). Additionally, remote headwater catchments like the subject of this study are rarely instrumented to begin with. A California-based study of post-wildfire debris-flow initiation found a successful method of model calibration in spatially adjusting infiltration capacities to allow for the model to represent the heterogeneous spatial nature of burn severity (McGuire et al., 2018). The Ages model allows for similar spatial distribution mapped to various model parameters based on groupings of soil classes. This method is discussed in a later section when applied to the Ages Bennett Creek Model.

Another significant challenge is obtaining the proper frequency and scale of precipitation data to drive hydrologic models. Gridded Quantitative Precipitation Estimates (QPE) datasets like MRMS (Multi-Radar Multi-Sensor) from the National Oceanic and Atmospheric Administration (NOAA) National Severe Storms Laboratory (Zhang et. al., 2011) are widely used due to their spatial and temporal coverage (Partridge et al, 2024). MRMS combines data from radar networks and rain gauges to generate high-resolution precipitation estimates that are critical for modeling storm events in burned watersheds (White et al., 2023). Post-fire hydrology is often dominated by short, high-intensity rainfall events, making high-resolution datasets like MRMS essential for accurately capturing the flashy runoff regimes typical of post-fire landscapes. However, uncertainties in gridded precipitation data, particularly in areas with complex terrain, can introduce errors into hydrologic simulations (Derin and Yilmaz, 2014; Stampoulis and Anagnostou, 2012; White and Nelson, 2020). This limitation underscores the need for models that can adapt to variability and uncertainty in precipitation inputs while leveraging the strengths of gridded datasets.

Meteorological stations are often sparse (or nonexistent) in burned watersheds due to damage by fire and/or sparse coverage in remote areas regardless of fire. Despite these challenges, advances in gridded precipitation and datasets and semi-distributed hydrologic models have improved the ability to model post-fire responses under data-limited conditions. In a study conducted in Colorado's Front Range comparing satellite-based QPE, radar-based QPE, and rain gauges, it was noted that satellite-based QPE outperformed rain gauges in simulating streamflow, and that radar-based QPE outperformed both satellite and rain gauge data (Moreno et. al, 2012). Two studies have tested and demonstrated that MRMS is quite accurate in Colorado, suggesting that distributed QPEs can perform much better than direct observations extrapolated over an area (White and Nelson, 2020; White et al., 2023).

The European Centre for Medium-Range Weather Forecasts (ECMWF) produces multiple reanalysis dataset products, where many observations over a vast network are used as inputs to a model that produces gridded climate timeseries across vast regions. A study located in Patagonia, Chile, evaluated a hydrologic model using observed precipitation data versus a climate reanalysis dataset from the ECMWF known as ERA-Interim. Using parameterization from a model applied to a similar region in western Canada, the model using the ERA-Interim climate data significantly outperformed the observational precipitation data (Krogh et. al., 2015). Another ECMWF dataset, ERA5-Land, was used to construct temperature models of the Green River in Utah and the Colorado River in Arizona. In this application, models using ERA5-Land (which is adjusted for elevation effects) outperformed those using direct observations that were extrapolated to surrounding areas, also with adjusted for elevation (Mihalevch et al., 2022).

In a study conducted by Tarek et. al. (2020), ERA5 was used to model thousands of watershed across north America on a daily scale. The authors note that subdaily temporal resolutions and spatial resolutions of less than 30km is desirable because modeling in small watershed may not be feasible or possible otherwise, since entire rainfall-runoff events occur in timespans of less than one day (Tarek et. al., 2020). This is especially true in a post-fire setting, as decreased infiltration capacity would only serve to shorten the length of time of events. Tarek et al. cite the need for evaluation of hydrologic model performance on a subdaily timescale using ERA5 data as a continuation of their work, which this study accomplishes. Li et al. (2023) also stressed their use of high resolution inputs in the post-fire application of distributed models in order to capture the fine-scale variability of hydrology processes.

1.2 Site Description

Bennett Creek (Figure 1-1) is a headwaters stream in the Cache la Poudre River Watershed in Northeast Colorado. It is fed by intermittent streams through moderately steep terrain with rocky outcroppings and evergreen forest with intermixed aspen, wildflower meadows, and various brush. Its soils are dominated by gravely loam with intermixed regolith and shallow depth to bedrock (Soil Survey Staff).

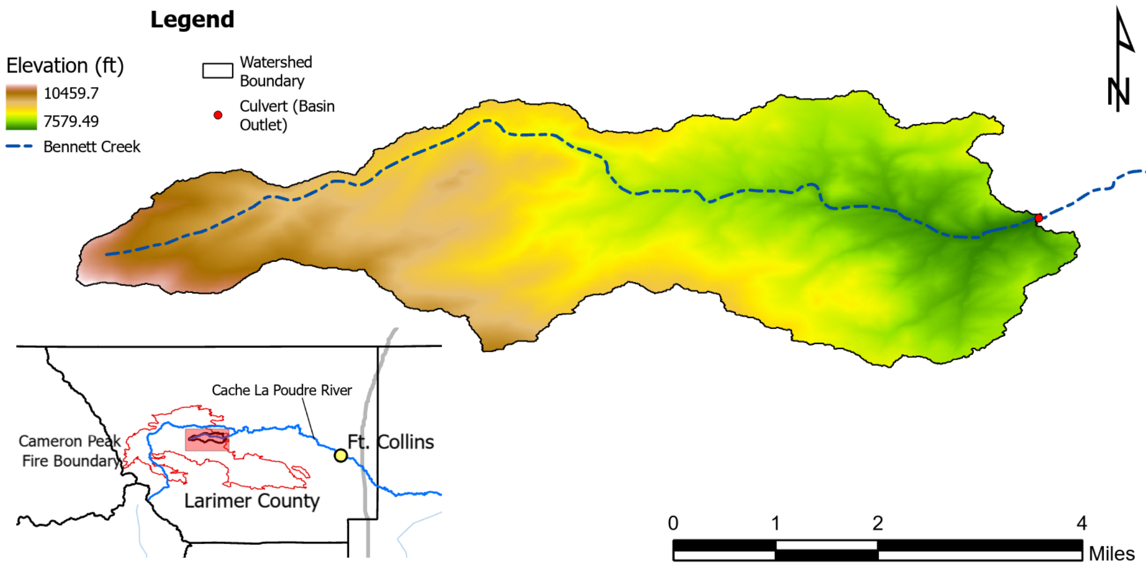


Figure 1-1 Map of study area depicting watershed boundary, main channel of Bennett Creek, and a digital elevation model (DEM) of the area. Inset map shows main map extent indicated by red highlighted area, and the Cameron Peak Fire boundary is outlined in red.

The main creek runs for approximately 8 miles before crossing under Forest Road 139 through a culvert where streamflow and precipitation are monitored by Larimer County. After passing through the culvert, Bennett Creek forms a gulch and flows for roughly 3.5 miles further before its confluence with the Cache la Poudre River. The study area (model domain) was defined as the catchment draining to Bennett Creek upstream of the culvert (Figure 1-1). This area is approximately 11.3 mi2 and rests between elevations of 7580 and 10,460 feet. The extreme change in elevation for a relatively small watershed area also poses a hydrologic modeling challenge.

The Cameron Peak Fire (See Cameron Peak Fire extent in Figure 1-1) burned over 5 months in late 2020 and consumed over 208,000 acres in Rocky Mountain National Park and the Roosevelt and Arapaho National Forests. Approximately 95% of the study area falls within the Cameron Peak Fire perimeter as determined by the USFS Burned Area Emergency Response (BAER) dataset (USFS 2014). See Cameron Peak Fire extent in Figure 1-1. For the purposes of this study, the 5% of the catchment outside the burned area was lumped in with areas within the burn perimeter that were classified as “unburned”. The breakdown of these classifications for the catchment, along with their definitions, are presented in Table 1-1 and Figure 1-2. The impacts of the Cameron Peak fire have been evident in this region beyond the initial fire impacts, producing flash floods and debris flows not far from the study area that collectively caused four fatalities and major damage to homes and roadways (Kostelnik 2021, Coloradoan 2023). Additionally, water quality was impacted by suspended sediment and ash downstream of the burn scar, forcing the disuse of the Cache la Poudre River as a drinking water source (Coalition for the Poudre River Watershed, 2022b).

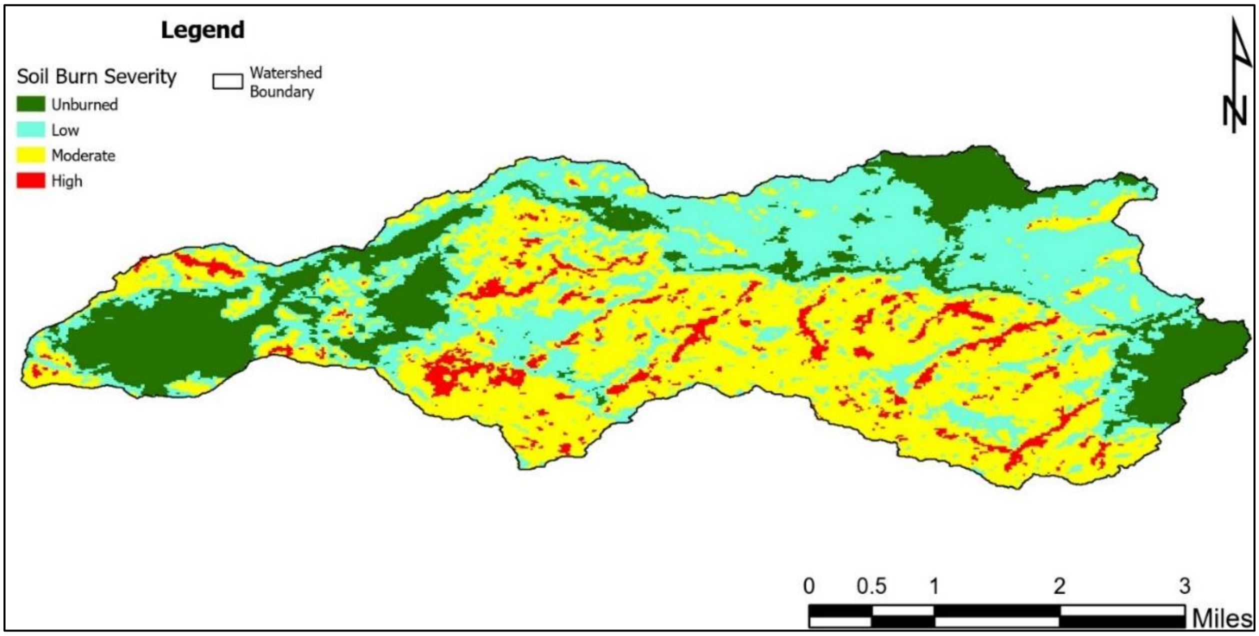


Figure 1-2 Map of USFS BAER Soil Burn Severity at Bennett Creek. (data from BAER database)

Table 1-1 Breakdown of Soil Burn Severity area within Bennett Creek catchment with definitions adapted from BAER Field Guide for Mapping Post-Fire Soil Burn Severity. (Parsons 2010)

BAER Soil Burn Severity	mi^2	%	Definition
Unburned	2.2	19.8	~unburned
Low	3.9	34.3	~Organic layers like litter remain mostly intact, even if charred. ~Canopies and understory vegetation often appear "green". ~Soil retains its natural structure, providing protection against erosion due to intact vegetation and fine roots.
Moderate	4.6	40.5	~Up to 80% of pre-fire ground cover might be consumed. ~Site often looks "brown" from scorched vegetation. ~Soils have a heightened erosion risk after rain due to reduced vegetation cover and potential root mortality.
High	0.6	5.3	~Nearly all pre-fire ground cover, including vegetation litter, and duff, are consumed. ~The site predominantly appears "black" from extensive charring. ~Over 75% tree mortality, 100% crown charring, herbaceous plants mostly charred/consumed ~Bare soil, vulnerable to high erosion and run-off, especially during rainstorms, due to lost vegetation and affected soil structure.

A multifaced group of municipalities, watershed coalitions, federal agencies, CSU, and other partners have been involved with the fundraising, implementation, and monitoring of the largest scale aerial mulching application project in the United States to date. From summer 2021 to fall 2022, over 17 square miles were mulched in the Cameron Peak burn scar, which along with other restoration efforts costed over $22 million (Coalition for the Poudre River Watershed, 2022a & 2022b). Mulch was dropped from helicopters after being loaded at staging areas due to the remote, steep, and rocky nature of the region, preventing access for large vehicles. Within the Bennett Creek catchment, 1.3 square miles of mulch were applied in 2021, and another 0.5 square miles in 2022. Six experimental watersheds were established within the Bennett Creek catchment in 2021. Half of these watersheds had mulch applied, and the other half were left as controls (Figure 1-3).

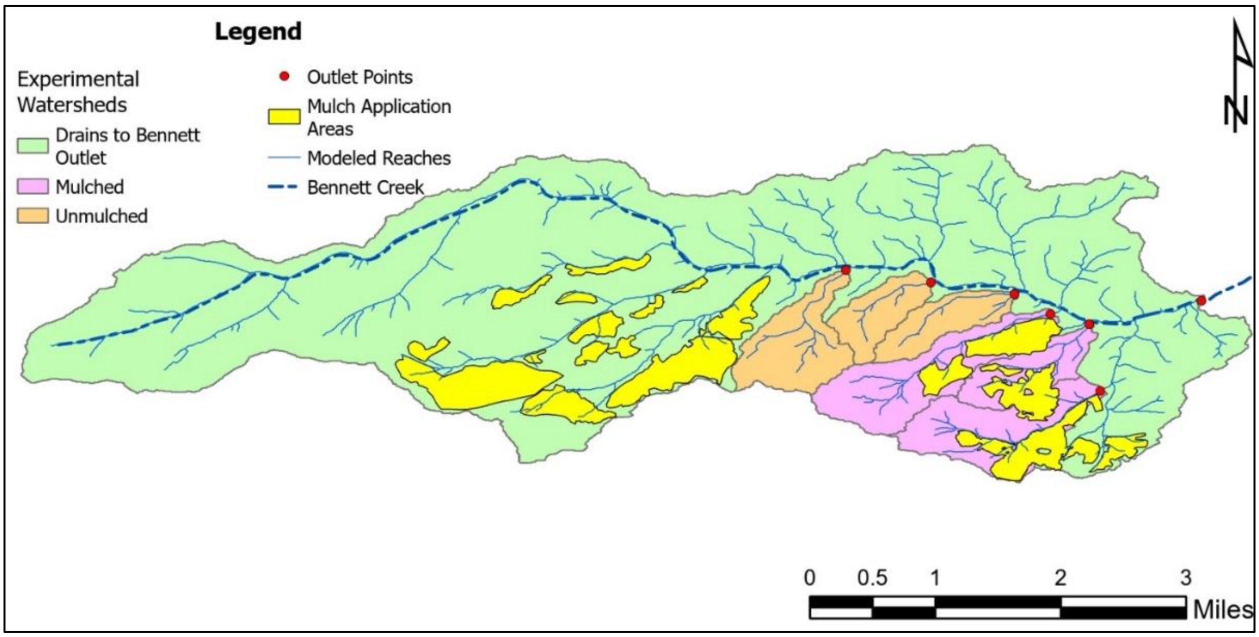


Figure 1-3 Experimental watersheds, modeled reaches, and mulch application areas within the Bennett Creek catchment. Yellow areas are where mulch was applied, orange areas are experimental catchments classified as “unmulched” controls, and the pink areas are experimental catchments classified as “mulched”. The green area is the remainder of the area that drains to the Bennett Creek outlet culvert.

A study of the six experimental watersheds using structure-from-motion drone imagery to construct high resolution digital elevation models (DEMs) of the sites before and after sedimentation-producing storm events concluded that factors such as slope and rain intensity have a greater effect on sedimentation rates than whether or not there was mulch applied to the catchment or not treatment (DeLoss 2023; Murray 2023). That is, not enough mulch was applied to measure meaningful differences in this setting, and that perhaps more strategic placement or larger amount of mulch applied to a catchment would be a more effective. A study in the Bennett Creek experimental subwatershed was conducted to measure hillslope scale erosion using sediment fences and game cameras, which concluded that there was no observable difference from mulching treatments on the timing or generation of sedimentation (Geller, 2023). A site visit to of one of the experimental watersheds soon after mulching in summer 2022 illustrated the sparse ground coverage and shallow depth of mulch within the application areas, which is shown in Figure 1-4.

Figure 1-4 Photograph of recent mulching in a moderate/high burn severity zone. Note mulch coverage, charred tree remains, and natural regrowth of herbaceous and evergreen plants. Photograph taken by author.

1.3 Research Questions

The following research questions were developed in conjunction with our partners at USFS and USDA ARS:

- How effectively does gridded climate data at an hourly model timestep represent the complexity of hydrologic processes and peak flows in Bennett Creek in the seasons following wildfire?
- How do spatially distributed modeling techniques improve our understanding of fire-related hydrologic changes and resulting model representations?

- In what ways can MRMS rainfall data enhance hydrologic predictions for Bennett Creek, as compared to direct rainfall measurements?
- What insights into hydrologic response and runoff timing at the subwatershed level can subhourly data capture that hourly or daily data might miss, and how might these insights be useful to land managers?

1.4 Motivation for Research

The multiple dynamics at play, including fire impacts, revegetation, mulching treatments, and other human perturbations may complicate hydrologic processes beyond the already complex and highly variable hydrologic behavior of mountain landscapes. Having some context for how interplay of processes may ultimately affect downstream waterways gives land managers crucial context for projecting risk and planning restoration activities following a fire in mountain regions. Many of the areas effected by wildfire in Colorado and beyond are lacking climate-monitoring instrumentation, or instruments are damaged by the fires themselves. Additionally, many headwaters streams are very remote and difficult to access, or are otherwise not gaged, making it even more difficult for what to expect following a fire in the area.

Unfortunately, a gage was not installed at Bennett Creek until after the fire. The modeling framework below seeks to rectify this lack of information via simulation of revegetation dynamics in tandem with calibration of the model to a streamflow record that is limited both in extent and seasonality, as the gage was installed post-fire and is removed periodically in the winter. Another challenge to modeling in this study area is the lack meteorological sensor stations in the catchment area except for precipitation tipping buckets, and these tipping buckets are not evenly distributed or abundant within the study area. This relative sparseness of monitoring data given the spatial variability of rainfall in mountainous regions are insufficient to provide sufficient information to drive a hydrological model. Thus, gridded climate data products were obtained to supplement the empirical observations to enable construction of a hydrologic model. With this hydrologic model, the effects of revegetation of the burn scar are explored in the downstream hydrologic flow regimes.

Channel evolution in the experimental watersheds was too rapid for the establishment of rating curves (personal communication, Megan Sears)(Figure 1-5), and thus, channel discharge could not be computed at these locations. These limitations prevented the use of any of these data for parameterization of the model in regard to mulch treatments and were not usable to aid in model development or calibration.

Stage observations and photographic timeseries of sediment fences during rain events in summer 2022 indicated that a subdaily model would be required to capture the rainfall response dynamics at the site, where high rain intensity sometimes caused hillslope-scale sedimentation events to occur fully within an hour. So far, this has been attributed to the effects of fire, steep slopes, and potential for high rain intensities characteristic of the region. This highlighted the need to develop both an hourly and sub-hourly (5-minute) version of the model, if these smaller scale processes were to be explored in modeling exercises. Wells et al. (2024) also identified that subdaily temporal resolution is desired for more accurate rainfall-runoff processes in their post-fire study using Ages (Wells, 2024).

Storm event timing at the experimental watershed and subwatershed scale and potential peak flow forecasting at the catchment terminal outlet are being investigated to determine the viability of Ages modeling at various spatial and temporal scales. The primary benefit of this research was providing a data-based modeling tool that can be used to predict the impacts of fire on the hydrology of Bennett Creek. Disaggregation of runoff at the catchment's terminal outlet signal (or the decomposition of this signal into its constituent components or driving processes) from the highly variable precipitation and climate inputs is a very valuable tool for land managers, as information can be obtained from the model about what processes are occurring throughout different parts of the watershed.

Land managers normally use data collected onsite via instrumentation for current or historic analysis, but a model that uses gridded input datasets is a powerful tool for understanding hydrologic processes for future conditions in basins with limited instrumentation. For example, changes in the hydrologic processes as the burn scar revegetates can be simulated. This research enhances the current understanding of post-fire hydrologic modeling through the application of distributed parameterization and use of gridded datasets to produce a model that can represent post-fire processes and reasonably predict peak flows and event timing without direct measurements within the boundaries of the study area. As previously noted, mountainous environments and topography are very spatially heterogeneous, which can produce weather and hydrologic conditions that vary greatly over short horizontal distances. All hydrologic models are imperfect because the assumptions and simplifications made in modeling could never perfectly represent the complexity of processes at very small spatiotemporal scales, and no data source can perfectly capture the exact precipitation and climate patterns a given location actually experiences. For example, deviations from this exactly perfect precipitation record caused by topographic interference in radar-based measurements may produce errors in estimates of peak flows and event timing, or could lead to less than ideal parameterization during calibration.

Figure 1-5 Photograph of channel near outlet of an experimental watershed. Note steeply incised banks and bank erosion. Dr. John McCray for scale.

This investigation also serves as a foundation for further modeling at Bennett Creek as more information becomes available. For example, rigorous models could be developed to evaluate fire impacts if the following were available: data representing a measured effect of mulching treatments, additional measured climate data, and additional information such as soil moisture data that can be used to calibrate models. Additionally, sediment, nitrogen and phosphorus transport can be simulated in the future with the Ages platform given further data collection and model development. Watershed modeling efforts have not taken place at Bennett Creek in the past, and since it has been methodically managed as an experimental watershed with spatial controls on treatments, is an ideal location to parameterize a model that could serve as a proxy for the region.

Considering that either the mulching treatment was ineffective at Bennett Creek, or that the experiments designed to measure the effect were unable to detect any differences, more characterization of Bennett Creek is required to understand whether aerial mulching is a worthwhile treatment in this particular region. Once more data are collected that could help parameterize mulching effects, the model could be used for a burned watershed to determine where post-fire treatments can be applied to achieve the greatest benefit for the resources available. It could also be used before fires to estimate where post-fire treatments might need to be applied for the greatest benefit in important areas that are subsequently burned, or for which watersheds treatments are more or less likely to be successful. This will enable USFS and Colorado land managers and crews to be prepared to act quickly when fires erupt in watersheds that are crucial to Colorado surface water resources.

CHAPTER 2 METHODS

2.1 Data Collection & Manipulation

2.1.1 Climate: Gridded Timeseries Data

The Ages model requires climate data inputs in the form of time series for temperature, relative humidity, wind speed, solar radiation, and precipitation. All data types except precipitation were obtained at an hourly time interval from the ERA5-Land gridded climate database (Muñoz-Sabater 2021). This data source was chosen because of its high temporal and moderately high spatial resolution compared to many common gridded data products. ERA5-Land is robust in its estimation of climatic data on a global scale and is produced by applying atmospheric forcing and lapse-rate correction to ERA5, which incorporates thousands of data monitoring locations around the world at the land surface and in the near atmosphere. ERA5 is a modeled 3-dimensional global grid of many climate variables, created from observations across a vast network. It is a reanalysis dataset, meaning that the observations are fed through a model that produces estimations for grid cells without observation points. These time series were adjusted to fit 5-minute model temporal resolutions using linear interpolation. Era5-Land data are available on a 0.1x0.1° grid (Figure 2-1). For the long term warm-up period (an initial model run period that allows for model processes and storages to reach an equilibrium before starting the main analysis) of the model, which is discussed in a further section, daily climate inputs were obtained from University of California Merced Climatology Lab gridMET dataset (Abatzoglou 2013). Gridded Surface Meteorological Dataset (GridMET) is a daily gridded climate dataset that combines the magnitudes of climate variables from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) with temporal attributes of the North American Land Data Assimilation System (NLDAS-2) (both are daily climate datasets built from observations & cover the contiguous US).

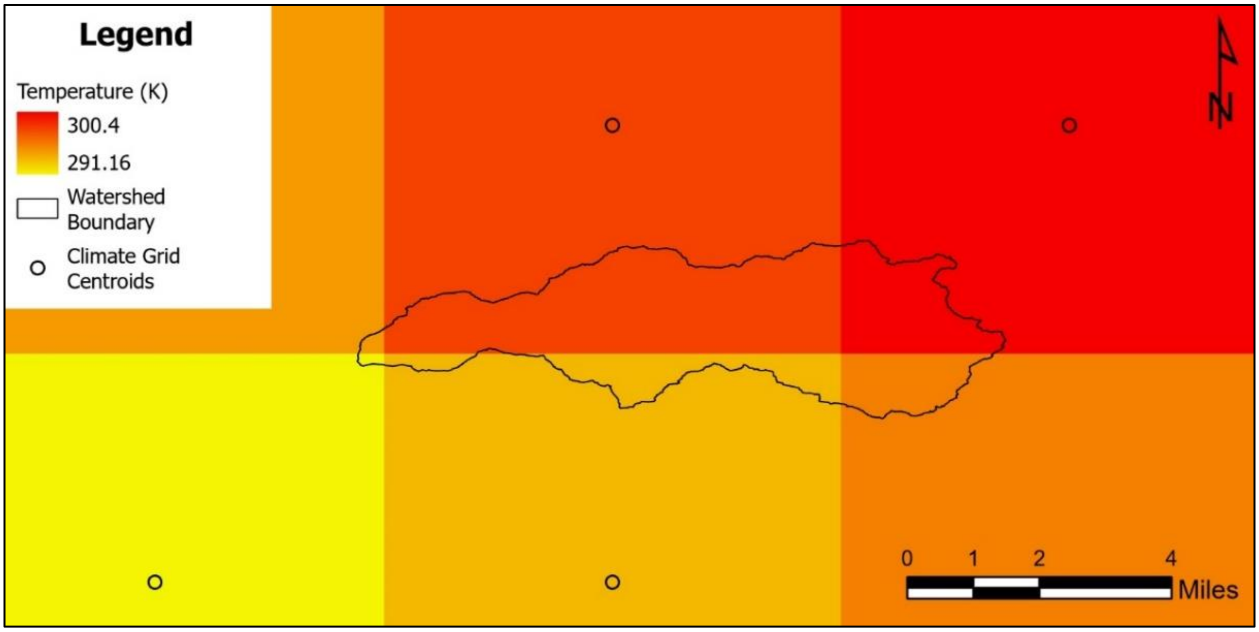


Figure 2-1 Map depicting spatial resolution of ERA5-Land gridded climate input data.

2.1.2 Precipitation Gridded Timeseries

A finer temporal and spatial resolution was desired for the precipitation inputs, so a 2-minute, 1km precipitation intensity was obtained from the NOAA MRMS dataset (Zhang et. al., 2011). These precipitation intensity data were interpolated to a 1-minute precipitation dataset that was aggregated for other temporal resolution runs. The reason for this approach was to preserve the greatest degree of detail in the temporal resolution of the precipitation data in hopes to improve model flow timing. These data were combined with breakpoint precipitation time series from five tipping buckets at the project site, and an additional 3 tipping buckets in and near the catchment, supplied by the Larimer County TriLynx NovaStar5 Operator Interface (Novastar Operator 2021). The Ages model uses a technique called regionalization to adjust climate and precipitation data based on a given HRU's proximity to a data station and difference in elevation. Values are subjected to a inverse distance weighing formula, where the further away a climate data station is from a given HRU, the less influence over the adjustment.

During preliminary model development, it was noted that the tipping bucket data caused decreased model performance, even using regionalization approaches. The tipping bucket data produced erroneous runoff events that were not present in the observed flow timeseries, which is attributed to the high spatial variability of rainfall across the region. The increment in which the tipping buckets record precipitation is much higher than MRMS (1mm vs ~0.0005mm) and was not in good agreement with MRMS rain timing or magnitudes. For this reason, only MRMS gridded precipitation data was used in model development, calibration, and assessment. Figure 2-2 is a plot comparing an additional set of two quality control tipping buckets to the nearest MRMS data that were installed in one of the experimental subwatersheds in summer 2022. MRMS data consistently underpredicted the amount of rainfall observed at these two reference gauges. Quality control tipping bucket data could not be imported directly into the model since the data collection began in 2022. Thus, quality control tipping bucket data was used to make a scalar adjustment to MRMS gridded data to provide more location-specific realism. The cumulative difference in precipitation between the two quality control buckets and their nearest MRMS grid locations over summer 2022 averaged 14%. Significant performance improvements were also noted early in model development from applying a 14% scaling factor to the gridded MRMS precipitation dataset. Locations of these precipitation measurements are shown in Figure 2-3.

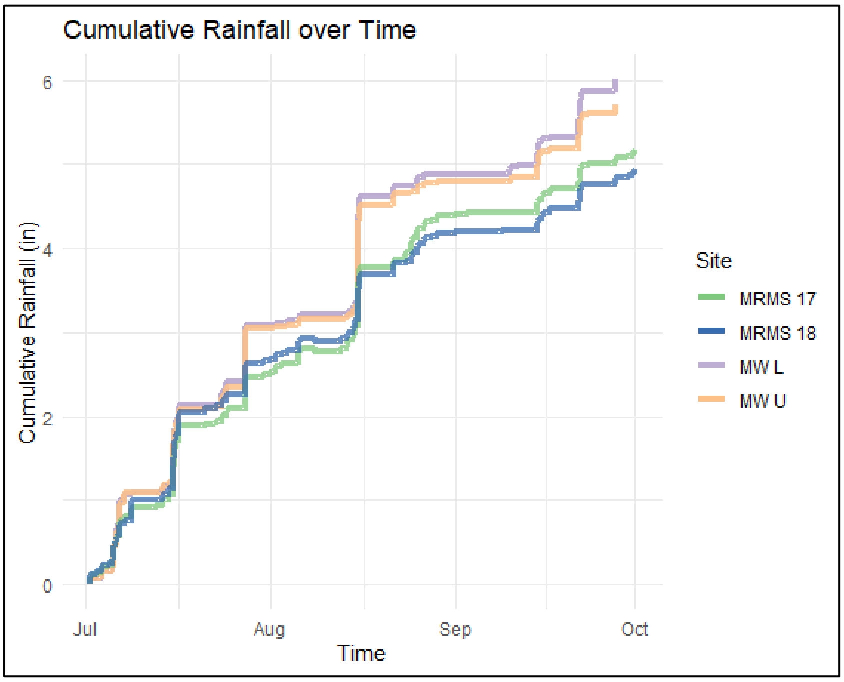


Figure 2-2 Plot of rain gages at Mulch West experimental watershed, upper and lower, compared to their nearest MRMS grid points, cumulative rainfall over summer '22, showing general validation of MRMS dataset and providing a scaling adjustment factor of 14%.

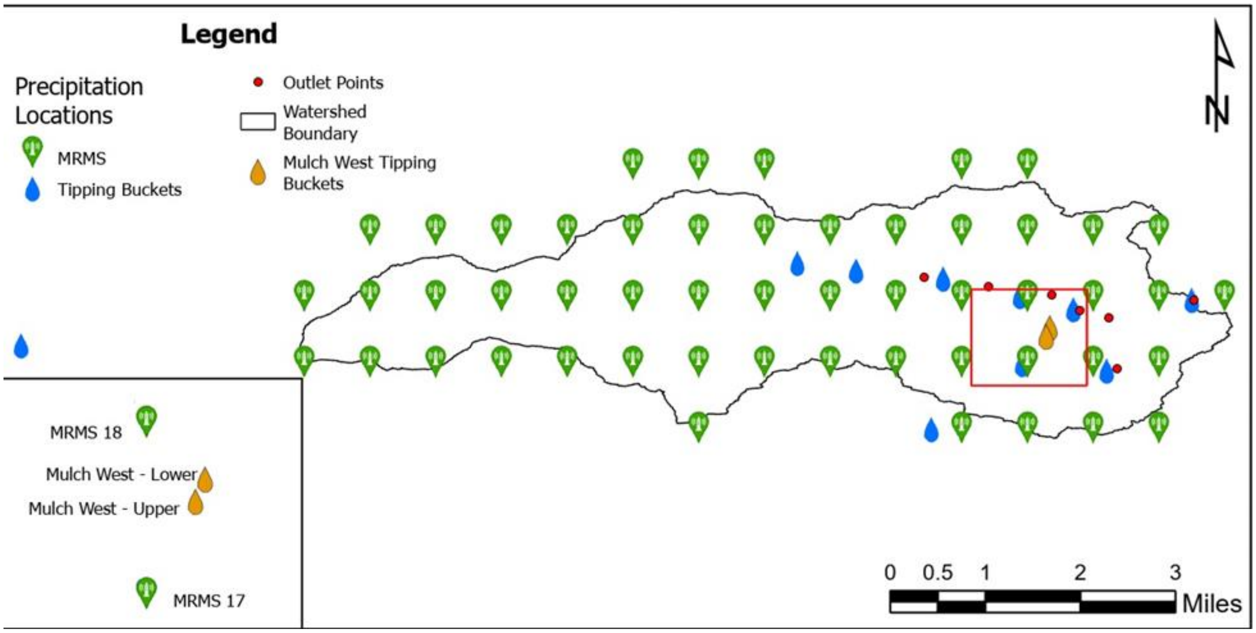


Figure 2-3 Map depicting the locations of experimental watershed and terminal catchment outlets, tipping bucket precipitation sensors, and MRMS gridded precipitation points relative to the catchment boundary.

2.1.3 Observed Stream Flow & Tributary Stage Data

Streamflow data used to calibrate the model were also obtained from the Larimer County TriLynx NovaStar5 Operator Interface (Novastar Operator 2021). This period of record began in June of 2021, the spring after the fire. The gage is either removed or powered off during winter conditions, and the first two years of data from this gage were used in this study. This limited record of flow is much shorter than what is normally used to calibrate a daily hydrologic model, which is typically on the order of decades in order to account for interannual precipitation variability (Teng et al., 2011). Some studies have found that daily SWAT and ATS models can be reliably calibrated for predicting short-term runoff with only a few years of streamflow observations, and in some wet regions as little as one wet season of observations (Jiang et al., 2024; Sun et al, 2017). The gage records a data point every time a change in stage of 0.2 feet or higher occurs, plus at the top of each hour. Flow data were interpolated to a 1-minute timeseries and then summarized into 5-minute and 1-hour timeseries. For the hourly calibration of the model, the number of observations present in the two summers following the Cameron Peak fire is roughly equivalent to 15.5 years of daily streamflow records, though it is noted that these two summers worth of data are unlikely to represent the interannual variability of conditions in the mountainous environment of Bennett Creek, let alone any enhanced variability caused by the fire.

Stage data were provided by Megan Sears from Stephanie Kamf's lab at CSU that were collected by her and her research team. These measurements were captured using staff gages with loggers which were deployed over the same season as the gage at the model's terminal outlet point, recording a measurement every 5 minutes. Because of the rapidly evolving shape of the channels in the experimental sub-catchments, the stage data included many noisy sections and the datum, or the baseline stage during dry periods, was shifted significantly. The high variability and noise inherent in these timeseries required that the timeseries was manually cleaned and adjusted using Microsoft Excel. All input data were cleaned, manipulated and prepared using R, Python, ArcGIS Pro, and Microsoft Excel.

2.1.4 Spatial Data

HRUs within the model were generated using the Catchment Areas Delineation Tool (Cadel)(Olaf, 2018). Cadel uses a 10m-resolution digital elevation model (DEM) obtained from the United States Geologic Survey (USGS) to create slope and aspect rasters for the full study area. With these data combined with the location of the catchment's terminal outlet and outlets of the experimental subwatersheds, CADEL generated HRUs for the study area iteratively. First, HRUs were delineated for the area outside the experimental subwatersheds, and then again inside these catchments. Smaller HRUs were generated inside the experimental catchments to eventually model hillslope scale processes at this location. HRUs are depicted in Figures 2-4 and 2-5.

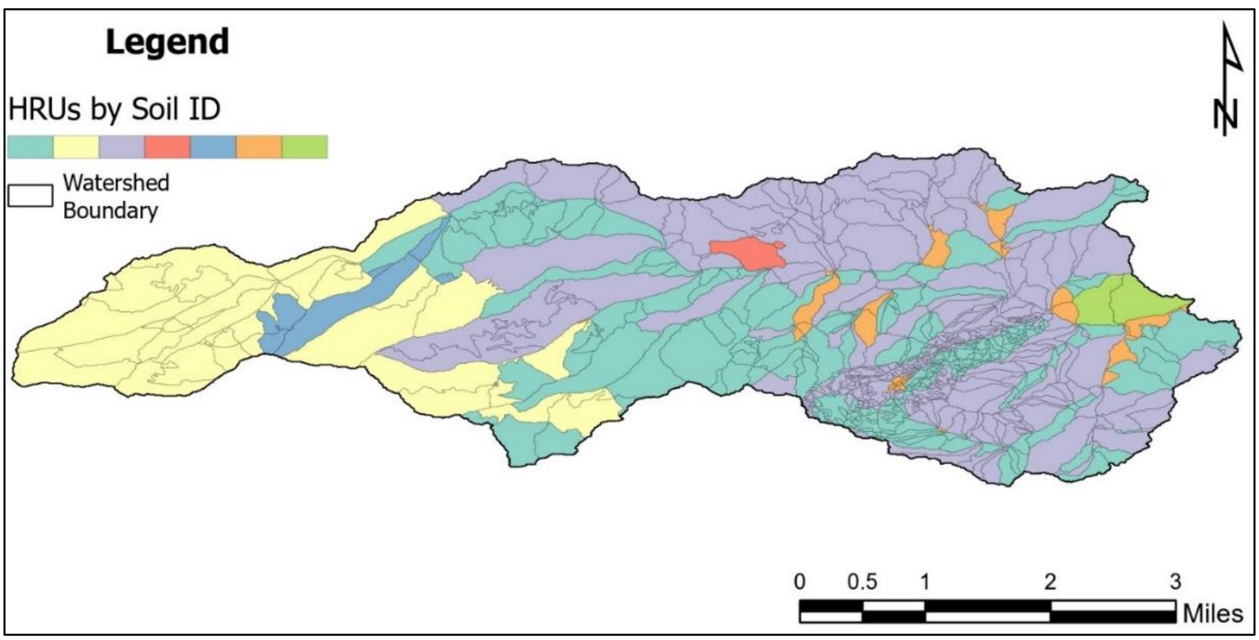


Figure 2-4 Map depicting modeled HRUs, colored by soil ID. Soil IDs were assigned to HRUs with similar soil characteristics.

Crop types for the study area were determined using the LAMPS tool (Kipka et. al, 2016), which intersects HRUs with NASS Cropscape data (Kipka et al., 2013; USDA, 2021) and returns the dominant crop type for each HRU. This tool determined the full study area to be composed of either coniferous forest or brush (Figure 2-5). Default parameters from the Ages model for crops were used other than maximum leaf area index (LAI), which was adjusted based on estimates made by USDA Ecohydrology staff over numerous field visits (Dave Barnard, personal communication). LAI is not fixed throughout model simulations but is a state variable that is simulated based on crop growth parameters like maximum LAI. Information required to build the Ages soils input file was obtained from the SSURGO soils database (USDA Soil Survey staff) including soil horizon thicknesses and saturated hydraulic conductivity, among other physical parameters. HRUs were sorted according to their predominant soil classes from SSURGO to assign soil parameters such as layer thicknesses, air capacity, field capacity, and dead capacity so that HRUs share those similar characteristics. Figure 2-4 illustrates these various soil groups of similar properties grouped by color.

2.2 Burn Severity HRU Classification

It has been noted in the past that representing burn severity is important for understanding the fire-induced alterations to hydrologic processes (e.g. Moreno et al., 2020). To represent fire-related changes to vegetation and soil related hydrologic processes in the model, the USFS BAER program's gridded Soil Burn Severity data were selected. This dataset was created from satellite imagery from before and after the fire and consists of a Burned Area Reflectance Classification (BARC) on a 30-meter grid within the burn perimeter (Figure 1-2). This dataset was selected for this study because of its gridded nature and because data for each fire are validated by USFS crews in the field (USFS, 2014). Fire intensity is defined in terms of vegetation and soil impacts. ArcGIS Pro was used to overlay these data with the map of HRUs to determine the dominant burn severity within each HRU. HRUs with dominant soil burn severities of Moderate and High were selected as "burned", so that the effects of fire could be represented in the model as adjustments to vegetation, soil, and hydrogeology parameters, as detailed in the modeling framework in the following section, and depicted in Figure 2-5. Refer back to Table 1-1 for descriptions of soil burn severity. Moderate and high severity burned HRUs were selected to be represented in the model as burned because low severity burns have limited impacts to soil properties, interception storage, and evapotranspiration as compared to medium and high severity burned areas.

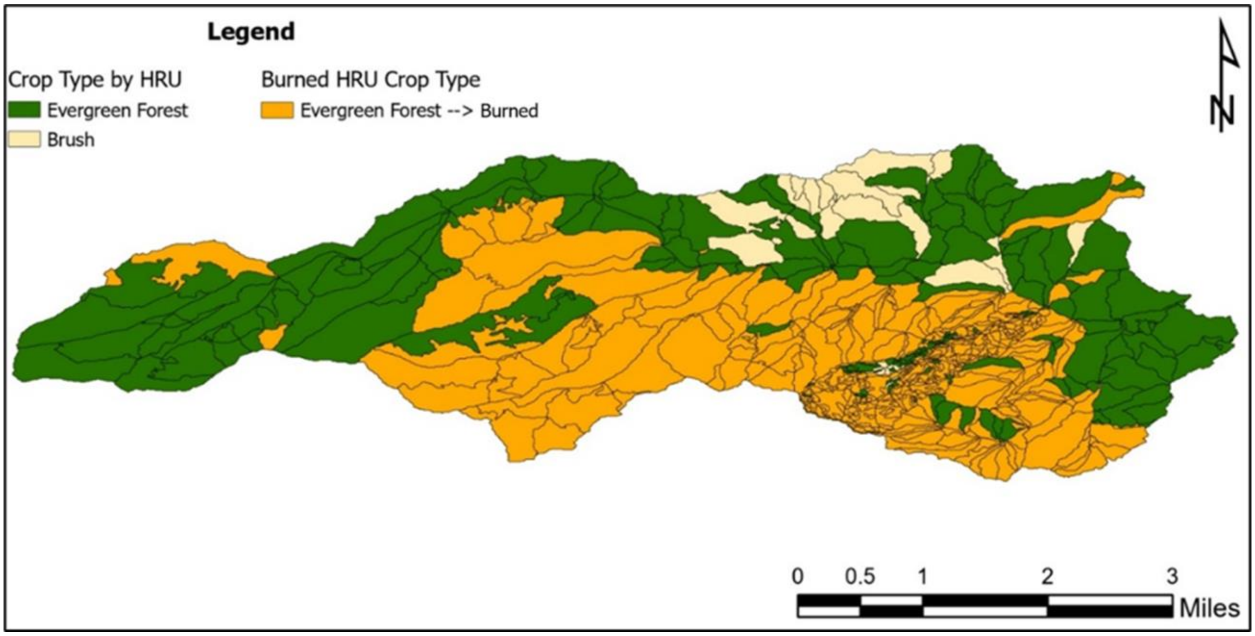


Figure 2-5 Map depicting modeled HRUs colored by crop type. HRUs colored orange contained majority moderate and high soil burn severity and were assigned as "burned". These HRUs were all determined to be evergreen forest prior to fire, but were modeled as brush, grass, or fallow following the fire.

2.3 Ages Model & Bennett Creek Model Development

Ages has the ability to save and load state files into the model that act as a snapshot of the various components of the hydrologic cycle and vegetation at a given time. Exploiting this feature, along with the flexibility of running at different time steps, the model was spun up over a long simulation period using daily data in order to build up the vegetation layers that would be present before the fire burned (Figure 2-6). Thirty years of daily climate data from 1990 through 2019 were used to build up this state by re-running the daily model until the state represented a 150-year old forest. This state was then saved and loaded into the subdaily model runs to provide initial conditions. These modeling frameworks allowed for the simulation of fire and revegetation at the site, where vegetation was removed from moderate-high severity burn areas in the model at the time of the fire in late 2020, followed by vegetation being allowed to fill back in to those areas in spring 2021 in the model. All burned slopes were designated as forest prior to the fire. Burned south-facing HRUs were modeled as grass, while north-, east-, and west-facing HRUs were modeled as brush, based on general field observations.

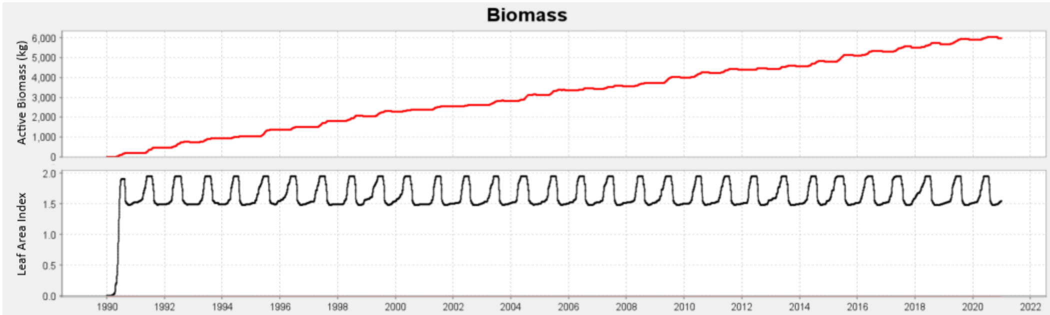


Figure 2-6 Plot of overall catchment active biomass and leaf area index during beginning of long-term daily warm-up period.

The highly complex, semi-distributed nature of the Ages model allows for representation of complex spatial and temporal variability across catchment that is characteristic of headwaters mountainous watersheds. It uses the Eagleson's infiltration model (Eagleson 1978), uses the soil saturation at any given time as a reduction factor on the maximum infiltration rate. This means that as soils become wetted, their infiltration capacity decreases. The model uses the Penman-Monteith equation (Monteith 1965) for its evapotranspiration calculations. These widely used models work in tandem with the high temporal and spatial resolution of the gridded input data obtained for the study to construct a model that represents infiltration processes. Figure 2-7 illustrates the general schematic of water routing through the Ages hydrologic processes for a single HRU.

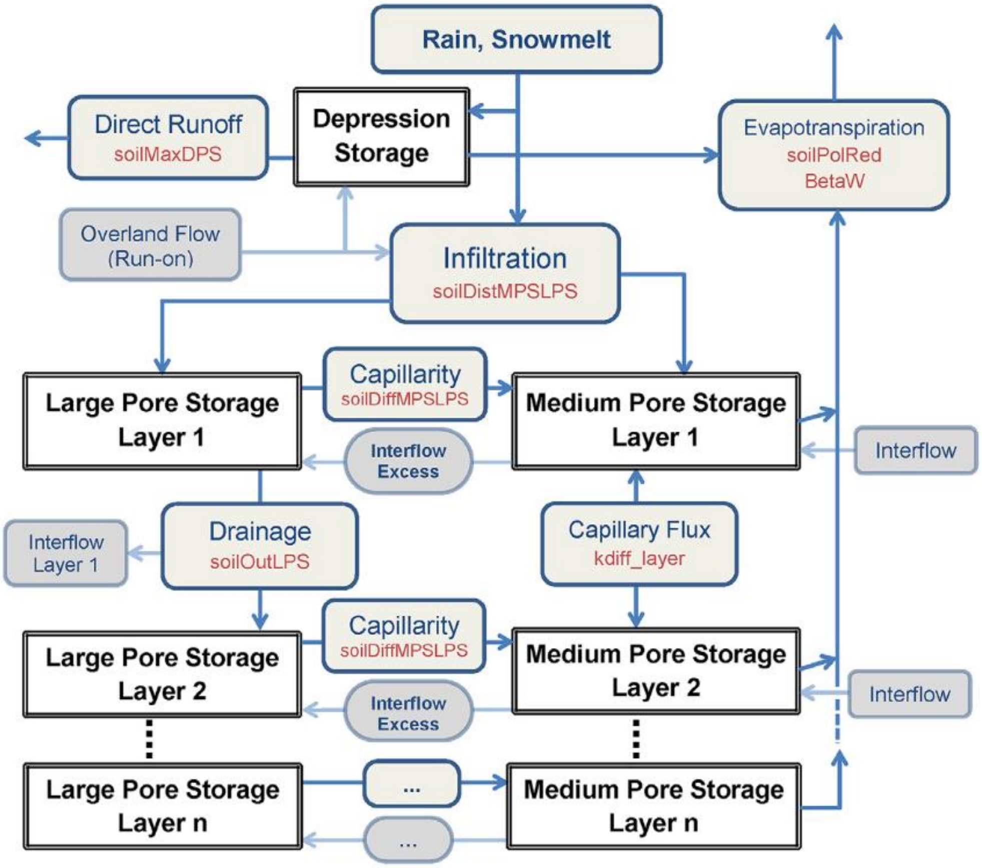


Figure 2-7 Schematic flowchart of hydrologic processes and parameters represented in Ages for a single HRU (Green et. al., 2015).

2.4 Calibration Methods

Calibration of the model was performed using Luca (Hay and Umemoto, 2006), which is a tool developed to run batches of model iterations to perform shuffled complex evolution (Duan, 1993). Shuffled complex evolution is a set of algorithms that sets model parameters to maximize performance against a statistical metric. Many model runs are generated where each iteration contains a set of certain parameters within specified ranges. These parameters are generally grouped into different components of the hydrologic cycle. For example, parameters involving evapotranspiration are grouped together, as well as those representing snow processes, infiltration, soil water movement, groundwater, and surface runoff. With each iteration of the model a statistical score is computed, and over many iterations, parameters sets are adjusted to improve the performance of the score. Over the course of the model's development, this process was repeated between adjustments to the model's crop parameters (adjustments to LAI based on field estimations), hydrogeology parameters (to better replicate baseflow periods in the record), and precipitation data (quality control scaling/forcing). Both the Kling-Gupta Efficiency (KGE) (Gupta et. al., 2009) score and the Nashe-Sutcliffe Efficiency (NSE) score were used separately as the objective functions to optimize model fit over the course of more than 20,000 model runs across 3 rounds for each calibration iteration. Calibrated parameters ranged across each process model, including parameters affecting ET, maximum soil infiltration rates, routing between various subsurface soil and groundwater storages, and timing lags for surface runoff and interflow. The model was calibrated to the discharge time series at the watershed's terminal outlet for the period of record (6/23/2021 to 10/1/2021), with the model calibration being validated for the period of record across summer (6/1/2022 to 10/14/2022). Table 2-1 contains a list of all calibration parameters along with a description and their units.

Additionally, Ages + Luca allows a modeler to define a set of overrides where HRUs can be subset according to a given class and with parameters being calibrated across those classes separately, if desired. This feature was exploited to allow Luca to calibrate certain parameters across classes of burned and unburned HRUs. Additionally, this feature was used to calibrate the hydraulic conductivity of top layers of soil, based on the HRU's burn status. Outcomes of both of these calibrations can be found in the Results section. Once the final calibrations were complete, the effects of burn parameterization were tested. Since no streamflow record exists before the Cameron Peak Fire, the unburned parameterization was applied to the full model area (including those represented as burned in the main model). This model run is graphically presented in the Results section.

Table 2-1 Full list of calibration parameters with units and additional information.

Parameter	**Unit**	**Description**	**Calibration step**	**Calibration domain**
ACAdaptation	unitless	Adjustment factor for air capacity (porosity)	Evapotranspiration	Global
FCAdaptation	unitless	Adjustment factor for field capacity (soil water content)	Evapotranspiration	Global
BetaW	unitless	Coefficient used to calculate transpiration in soil layers	Evapotranspiration	Subset: burned vs. unburned
soilPolRed	unitless	Polynomial reduction factor for reduction of potential evaporation with limited water supply	Evapotranspiration	Subset: burned vs. unburned
a_rain	unitless	Maximum interception storage capacity per leaf area index for rain	Evapotranspiration	Subset: burned vs. unburned

Table 2-1 continued

Parameter	Unit	Description	Calibration step	Calibration domain
soilMaxInf - Summer	mm/d	Coefficient used to calculate maximum infiltration in summer	Infiltration	Subset: burned vs. unburned
soilMaxInf - Winter	mm/d	Coefficient used to calculate maximum infiltration in winter	Infiltration	Global
soilMaxInf - Snow	mm/d	Coefficient used to calculate maximum infiltration under snowpack	Infiltration	Global
soilDistMPSLPS	unitless	Coefficient for distribution of infiltration to the large pore storage and medium pore storage	Infiltration	Subset: burned vs. unburned
soilMaxDPS	mm	Maximum depression storage capacity	Infiltration	Subset: burned vs. unburned
Kf	cm/d	Saturated hydraulic conductivity	Soil kf	Subset: soil ID; top layer only
soilOutLPS	unitless	Exponent for large pore storage outflow	Soils/Groundwater	Subset: burned vs. unburned
soilLatVertLPS	unitless	Cofficient for distribution of the large pore storage outflow on the lateral (interflow) and vertical (percolation) component	Soils/Groundwater	Subset: burned vs. unburned
kdiff_layer	unitless	Resistance parameter for capillary flow between layers	Soils/Groundwater	Subset: burned vs. unburned
soilDiffMPSLPS	unitless	Coefficient for the definition of the diffusion amount of the large pore storage storage in relation to medium pore storage at the end of a timestep	Soils/Groundwater	Subset: burned vs. unburned
gwCapRise	unitless	Capillary rise coefficient	Soils/Groundwater	Global
gwRG1Fact	unitless	RG1 (shallow groundwater storage) outflow coefficient	Soils/Groundwater	Global

Table 2-1 continued

gwRG2Fact	unitless	RG2 (deep groundwater storage) outflow coefficient	Soils/Groundwater	Global
gwRG1RG2dist	unitless	RG1 to RG2 gradient (distribution) coefficient	Soils/Groundwater	Global
geoMaxPerc	unitless	Maximum percolation rate to groundwater	Soils/Groundwater	Global
flowRouteTA	unitless	flood routing coefficient	Surface Runoff	Subset: burned vs. unburned
lagSurfaceRunoff	unitless	Surface runoff lag	Surface Runoff	Subset: burned vs. unburned
lagInterflow	unitless	Interflow Lag	Surface Runoff	Subset: burned vs. unburned

2.5 5-minute Rainfall-Runoff Analysis

Because rating curves could not be established to calculate runoff at the stage staff gages, model performance was evaluated using a timing-based approach using the following metrics: lag time, time of concentration, and time to peak, which are defined below. The observed stage records at the outlets of the experimental catchments were compared to representative reaches in the model along with constructed upstream precipitation timeseries from the MRMS grid. Model outputs from subwatersheds upstream of these reaches where staff gages were located were aggregated to sum the precipitation volume across those areas and converted back to rainfall depth using each location's drainage area. Precipitation-stage response lag times were calculated using both observed staff gage stage and model outputs from equivalent locations. Lag time is defined as the time from the maximum intensity of rainfall to the peak of the resulting runoff response (USDA, 2008). Precipitation time series were also generated for the furthest upstream HRU from each gage location to calculate the time of concentration for each experimental subwatershed, which is defined as the mean time for water to travel the longest flowpath to the gage location. Time of concentration is approximated in hyetograph analysis as the time from first precipitation in the most upstream location from the gage to the peak of the runoff response (USDA, 2008). The time to peak was also calculated for both observed and modeled flow data, which is defined as the time from the beginning of the runoff response to the peak of runoff (USDA, 2008). All measures of hydrologic timing were compared across the experimental subwatersheds to assess Bennett Creek 5-minute Ages model’s performance at estimating timing of flow, and to observe any differences between mulched and unmulched areas. Events were defined as any sudden increase in observed stage data in response to a storm. All timeseries were filtered to events where there was a rainfall-runoff response for both observed and modeled stage/runoff.

CHAPTER 3 RESULTS & DISCUSSION

3.1 Hourly Model Results

General processes related to vegetation and hydrology have significant differences across various locations in the watershed based on factors such as crop, elevation, and aspect. Examples are compared in Figures 3-1 through 3-3, showing crop and hydrologic processes in summer 2021 for representative HRUs. Previously established plants in the unburned HRUs begin with a significant above-ground biomass and leaf area, which gradually increases over the model period. The biomass and leaf area for the burned HRUs start near zero, and gradually increase. The burned HRUs had notably higher amounts of throughfall (less plant interception), which logically makes sense because the lack of leaf area on these HRUs prevent any interception losses. The proportion of precipitation that is intercepted increases throughout the growing season for burned HRUs as they revegetate, while unburned HRUs exhibit near constant interception and throughfall. Evapotranspiration fluctuates with precipitation for unburned HRUs, lagging a few days behind precipitation. In burned HRUs, evapotranspiration still follows precipitation, but since water is not retained as readily by soils in burned HRUs (which can be attributed to increased evaporation since there is no shaded canopy), evapotranspiration occurs more in pulses following larger rain events, where evapotranspiration only occurs for a short period following these large events. Surface runoff, normalized to a depth over the representative HRU area, was much higher for the burned HRUs vs unburned brush or forest. Without vegetation to intercept precipitation, and the potential presence of a hydrophobic surface soil layer, as soon as surface soil layers are saturated, water runs off over the land surface. Significant surface runoff was only observed in the unburned HRUs during spring snowmelt and some of the largest rain events of the summer, while runoff came with most rain events in burned HRUs. Model outputs were able to generally represent the vegetation conditions of the Bennett Creek watershed in a satisfactory manner.

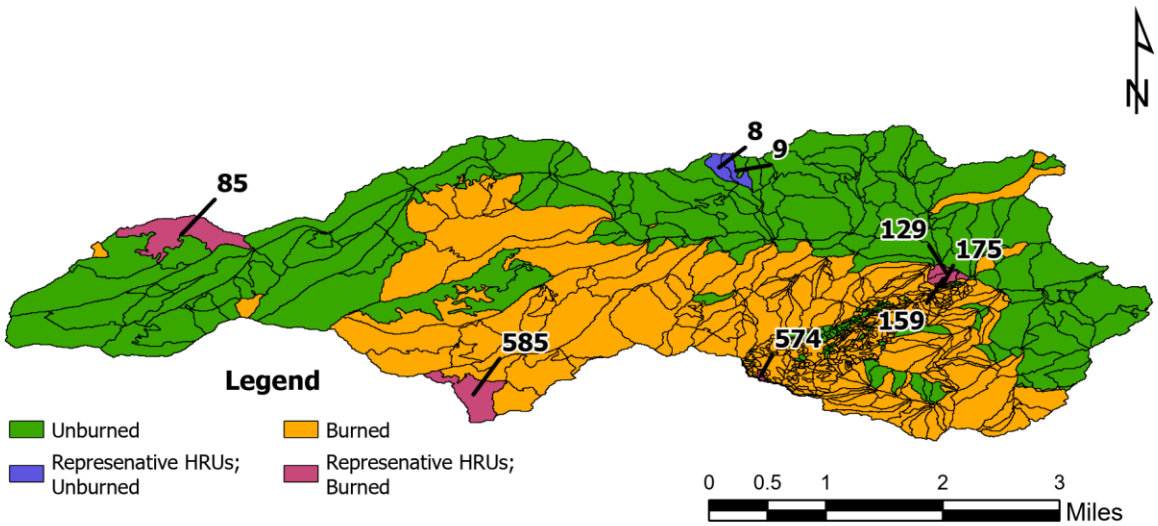


Figure 3-1 Map showing the locations of representative HRUs

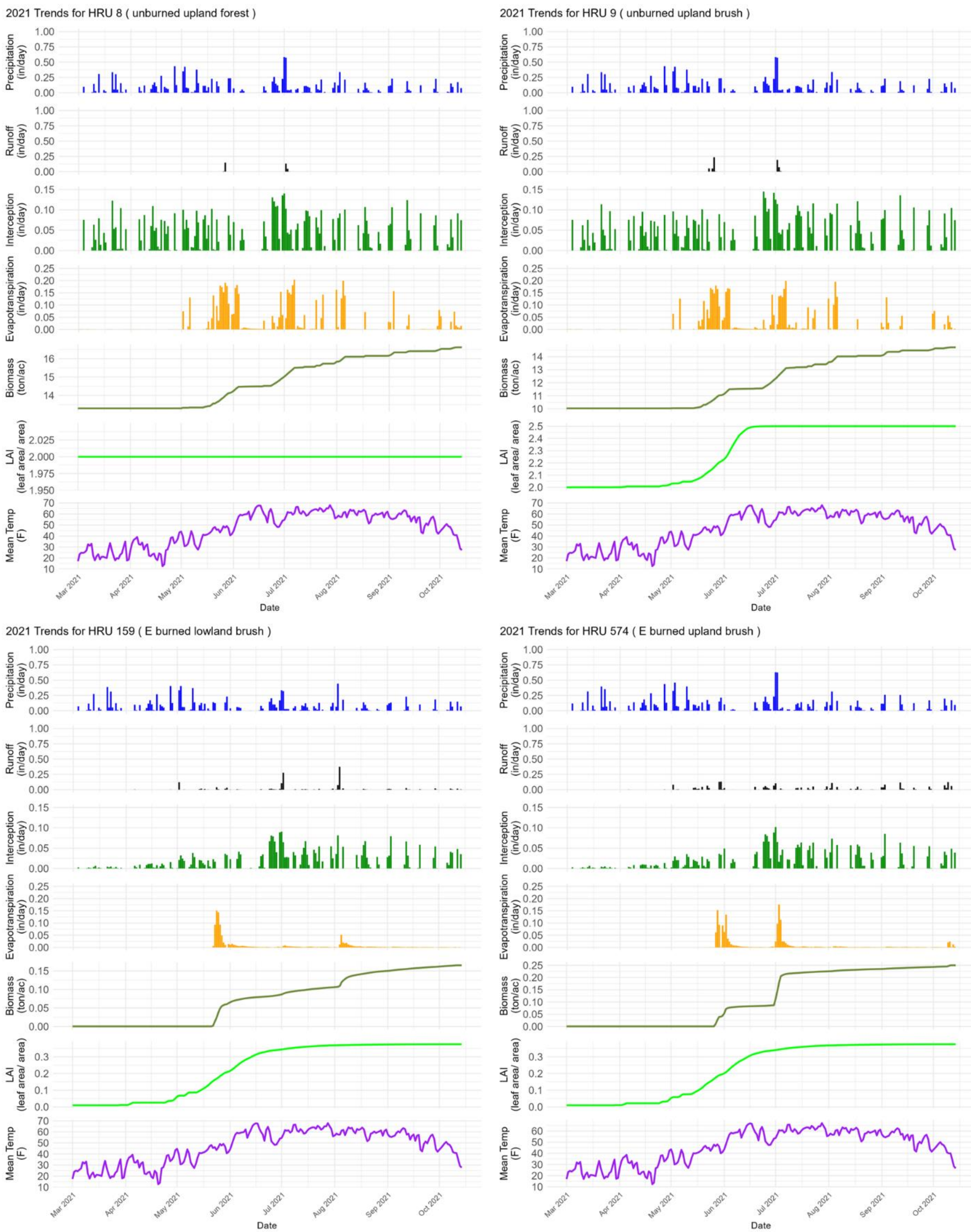


Figure 3-2 Plot of various modeled outputs for representative forest HRUs.

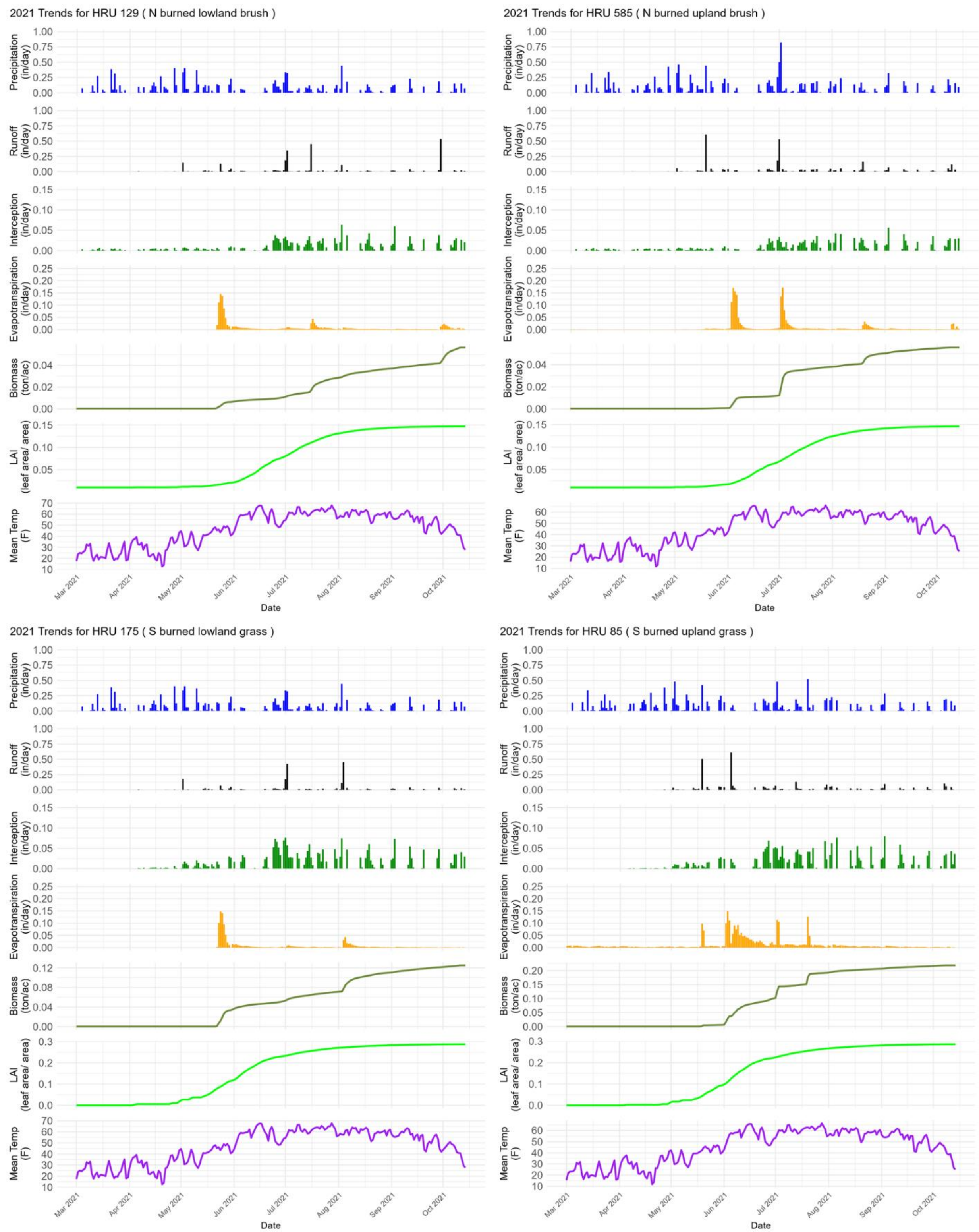


Figure 3-3 Plot of various modeled outputs for representative forest HRUs.

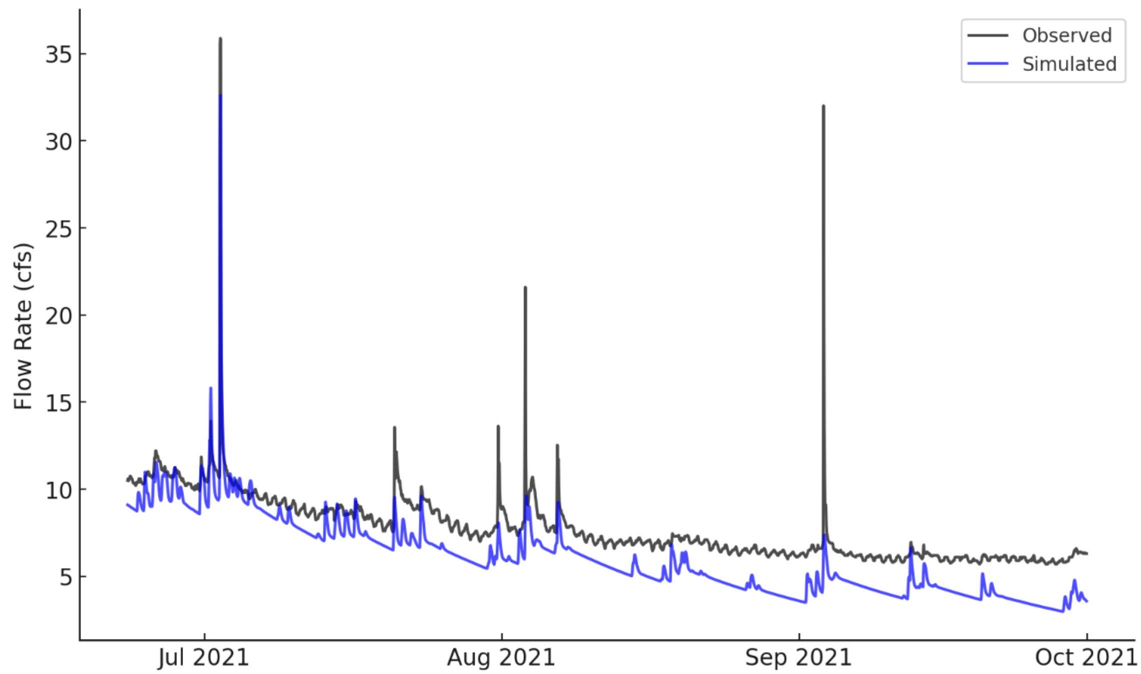
3.1.1 Calibration Performance

To assess the ability of the hourly model to predict hydrologic conditions in the watershed, various statistical metrics were applied to model calibration and validation periods for both the hourly model and its aggregated daily values. Two calibrations were attempted, one using KGE as the objective function and one using NSE. The calibration using NSE did not produce viable results, so KGE was used as the objective function for subsequent calibrations. The performance statistics used to score the quality of fit of the calibrated model are the KGE and NSE, percent bias (PBIAS), and Volumetric Efficiency (VE). KGE and NSE metrics compare the modeled values to observed values and give a score based on their similarity and range from negative infinity to 1, with 1 being a perfect fit between modeled and observed values (Gupta et. al., 2009; Nash & Sutcliffe, 1970)). VE ranges from 0 to 1 and is a measure of accuracy of the water balance of modeled vs. observed values (Criss and Winston, 2008). PBIAS ranges from negative infinity to positive infinity, and as a measure of bias, represents perfect model fit at PBIAS = 0% (Gupta et. al, 2009). Once the model was calibrated to an hourly time interval, results were also summarized at a daily timescale to allow comparison of model performance to models in other studies only run at this resolution. The performance statistics associated with these results are found below in Table 3-1. Indicators of quality-of-fit of the various scores are also included for quick reference (Harmel et al., 2018; Knoben et al., 2019; Moriasi et al., 2015; Rogelis, 2016). Note that these threshold values were not developed with subdaily modeling in mind, which is likely to produce lower performance statistics due to inherent higher variability. Performance thresholds have not been formally developed for KGE or VE, so the thresholds for NSE were applied as a proxy, with the acknowledgement that these scales are not directly comparable, as detailed above. These thresholds were only applied to aid in the relative comparison of performance between model scenarios.

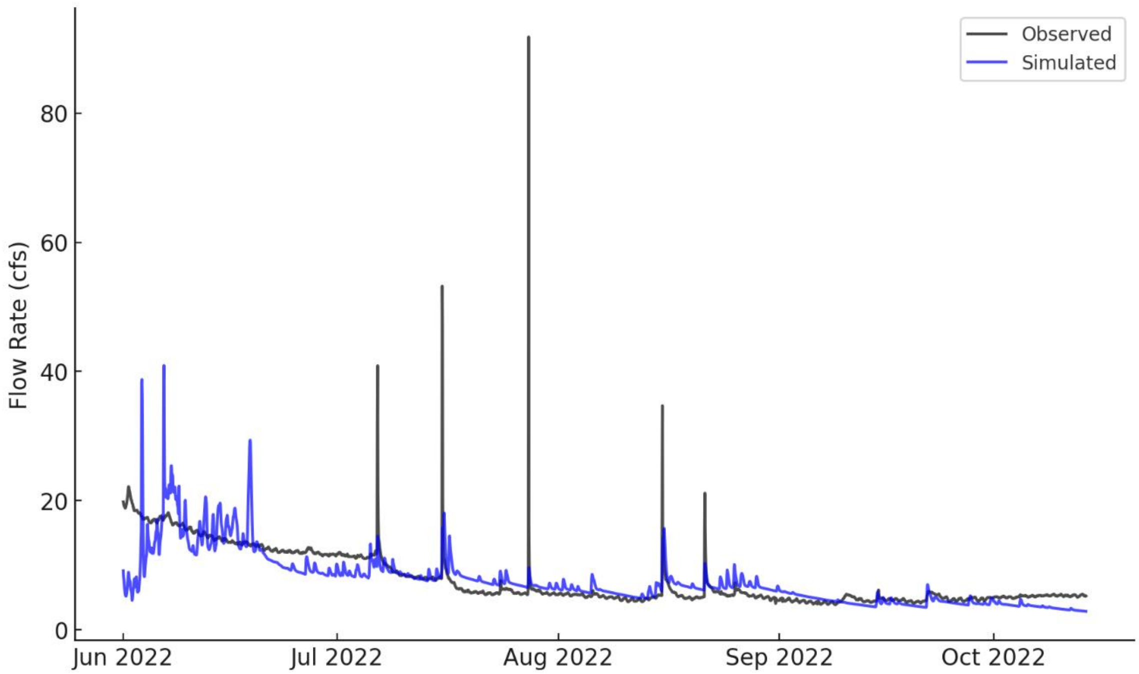
Table 3-1 Performance statistics for model calibration and validation at daily and hourly timescale. “P” = Poor, “S”=Satisfactory, “G”=Good, and “VG”=Very Good

Period	**Time Step**	**KGE**	**Quality of Fit**	**NSE**	**Quality of Fit**	**PBIAS**	**Quality of fit**	**VE**	**Quality of fit**
Calibration	Daily	0.68	S	0.00	P	-21%	S	0.79	S
Validation	Daily	0.81	G	0.66	S	-3.1%	VG	0.97	G
Calibration	Hourly	0.76	G	0.12	P	-21%	S	0.78	S
Validation	Hourly	0.70	G	0.47	P	-2.8%	VG	0.77	S

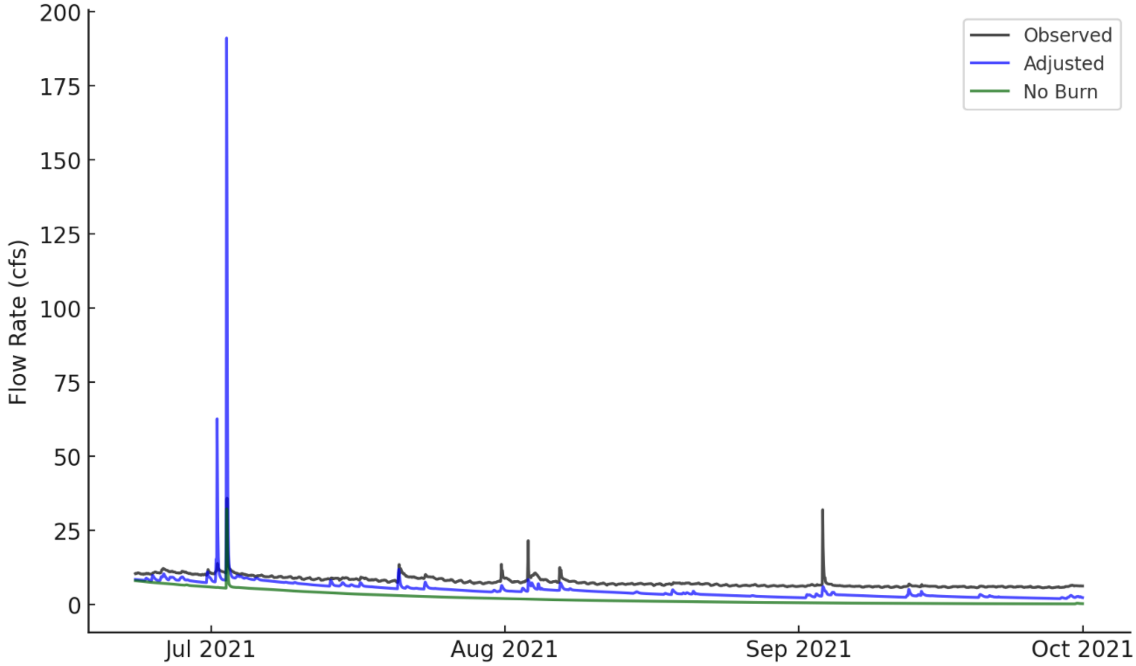
Figure 3-4 shows the results of this calibration and validation, with observed flows from the catchment outlet plotted against the simulated flows from the model using calibrated values. The model is estimating baseflow and storm recession periods fairly well and successfully captured the large event in July 2021 but could use improvement in peak flow estimation throughout the rest of the season. Model development and calibration could not produce a seasonal recession curve that matched the baseflow over the summer months, and the NSE metric suffered as a result, as it is sensitive to consistent over- and under-prediction. The validation period also features underprediction of peak flows but estimates periods of recession and baseflow significantly better than the calibration period. Generally, as shown in Table 3-1, the calibration and validation of the hourly model was satisfactory-very good for metrics other than NSE.



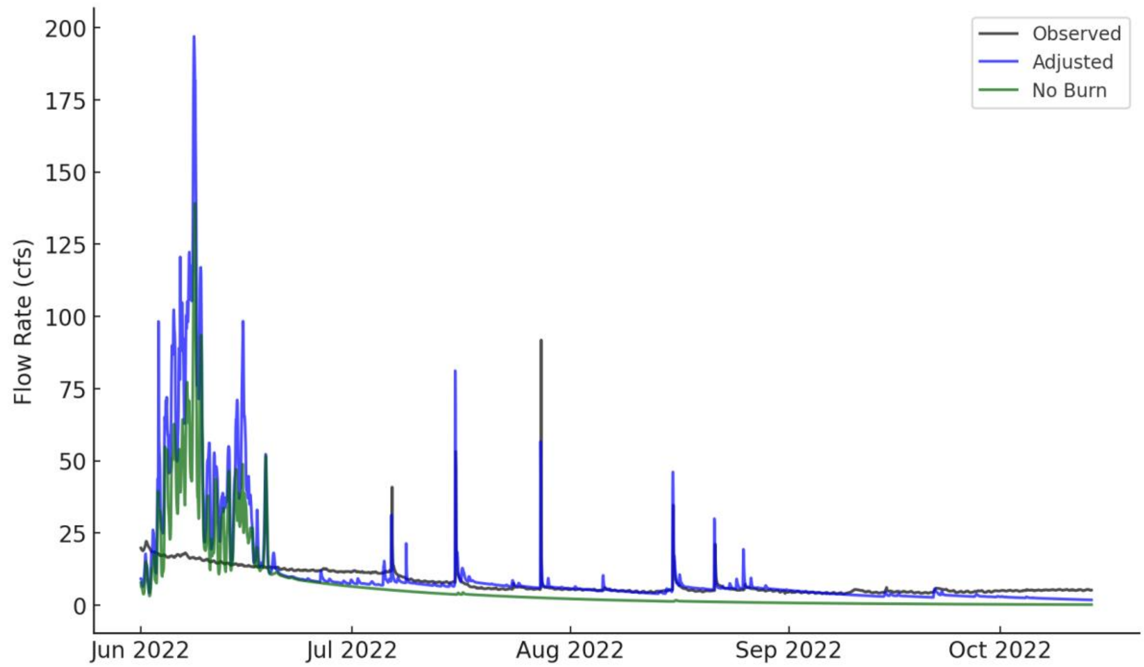
a) Calibration period resulting from Luca calibration.



b) Validation period resulting from Luca calibration



c) Calibration period resulting from calibration of soil Kf and an unburned representation of the model.



d) Validation period resulting from calibration of soil Kf and an unburned representation of the model

Figure 3-4 Results of an hourly calibration run adjusting global parameters. Subdaily timeseries of simulated vs observed flow at the modeled Bennett Creek catchment outlet. A: Calibration period resulting from Luca calibration. B: Validation period resulting from Luca calibration. C: Calibration period resulting from calibration of soil Kf and an unburned representation of the model. D: Validation period resulting from calibration of soil Kf and an unburned representation of the model

To improve the model's representation of peak flows, a calibration scheme was introduced that grouped HRUs as burned or unburned, and the top burned soil layer's hydraulic conductivity was allowed to vary from the original SSURGO values. Burned HRUs ultimately saw a large decrease in hydraulic conductivity, as shown in Table 3-2. This change ultimately reduces the burned HRU's infiltration rates and causes a more sudden increase in surface runoff (Figure 3-4c and 3-4d).

Table 3-2 Hydraulic Conductivity by Soil ID; Unburned values from SSURGO and calibrated for burned HRUs

Soil ID	Unburned kf (cm/day)	Burned kf (cm/day)	Difference (cm/day)
1001	244	6	-238
1201	244	6	-238

Table 3-2 continued

Soil ID	Unburned kf (cm/day)	Burned kf (cm/day)	Difference (cm/day)
1401	244	6	-238
1501	79	6	-73
1601	79	-	-
1701	244	6	-238
1901	244	-	-

Table 3-2 shows the improvement in peak flow percent bias to be 21% for the calibration period, and 69% for the validation period. This model adjustment of hydraulic conductivity in the burned areas resulted in significant improvement in model results, where underprediction of peak flows were resolved to a slight overprediction. During the calibration period, model calibration was not able to rectify the large overprediction of the first runoff event in summer 2021, nor was significant runoff produced from the subsequent summer 2021 events. While this is a unfortunate result, model results are improved significantly for the validation period. This poor performance during the calibration period could perhaps be caused by MRMS data straying further from reality, or from the presence of a thicker ash layer at the start of the summer, which could absorb more precipitation, and then have less of an effect as it washes away. If the latter possibility were the actual cause, then it could potentially be resolved using temporal variations in surface soil hydraulic parameters, which commonly used hydrologic models cannot simulate. Because the reasons could not be confirmed, and because additional model development and alteration were deemed beyond the scope of this small research project, this issue was not addressed further in this research. Until this aspect of the model's performance can be improved, the model is not an effective tool to be applied to flood forecasting or modeling. However, much can still be learned from using the model in its present form.

Peak flows may not be perfectly represented in the model, but Figure 3-4c and 3-4d illustrates that the burn parameters applied in the model make a notable difference in the hydrologic response to rainfall at Bennett Creek. With unburned parameterization applied to the whole watershed area, runoff events are effectively prevented except during the largest storm, which was the first storm of summer 2021. Under the unburned scenario vs. peak flow of this storm's peak flow was reduced by roughly 60%. In the summer of 2022, peak flows are effectively reduced entirely by simulating vegetation in the whole watershed. This demonstrates that the burn parameters being applied to burned HRUs cause a significant increase in runoff and are significantly different from the starting parameters.

Table 3-3 Percent bias for lower 50% of observed flows and peak flows

Time Period	**Soil kf**	**Lower 50%**	**Peak Flows**
Calibration	From SSURGO	-31%	-57%
Calibration	Calibrated for peak flow	-37%	36%
Validation	From SSURGO	1.4%	-70%
Validation	Calibrated for peak flow	-14.7%	1%

3.1.2 Performance Compared to Previous Research

Previous studies, similar to this research, aimed to better understand the hydrologic changes following wildfire events. The relevant processes includes increased surface runoff, changes in evapotranspiration, and the overall impact on the watershed's water balance. Each study employs hydrologic modeling to simulate watershed responses post-fire. There is a shared emphasis on the necessity of calibrating models based on observed data to enhance prediction accuracy, particularly in replicating peak flows and capturing the timing of hydrological processes post-fire. The studies listed below are compared with the results of this study, with the caveat that these studies used daily or monthly time discretization for analysis rather than the unique sub-hourly time steps used in this study.

The Bennett Creek Ages model is not yet performing quite as well as the Ages model developed for the Little Bear Fire of 2012 in New Mexico by Mankin et al. in 2022, wherein SNOTEL and Daymet gridded climate data were used as inputs. For that site, the Ages post-fire model attained a good fit for monthly averages (KGE=0.97) and daily flows (KGE=0.68-0.89). In another study, Havel et al. (2018) calibrated a daily SWAT2012 model in the Cache la Poudre watershed following the Hewlett and High Park fires, achieving a NSE of 0.81. Van Verseveld et al. were able to achieve calibration results of KGE = 0.9-0.96 in 2022 by using ERA5 data for climate inputs (except for precipitation) in a Colorado watershed, and used a radar-based product for precipitation, similar to this study, for a daily model.

This study, as well as the studies mentioned here all concentrate on understanding the hydrologic changes following wildfire events. This includes increased surface runoff, changes in evapotranspiration, and the overall impact on the watershed's water balance. Each study employs hydrologic modeling to simulate watershed responses post-fire. There is a shared emphasis on the necessity of calibrating models based on observed data to enhance prediction accuracy, particularly in replicating peak flows and capturing the timing of hydrological processes post-fire. This study's focus on both hourly and sub-hourly resolutions for capturing detailed process dynamics is more granular compared to the typically daily or larger timestep used in the studies by Havel et al. or the rest of the community.

Notably, these studies used daily or averaged data or monthly data. Temporal or spatial averaging of geological data almost always reduces the variability compared to data with finer discretization, and are thus typically results in better model calibration performance (Isaaks and Srivastava, 1990). The current study's focus on both hourly and sub-hourly resolutions for capturing detailed process dynamics, as well as finer spatial resolution than many hydrologic models is not common and represents an important first step toward simulating post-fire hydrologic responses at the appropriate temporal scale

Tarek et al. (2020) used ERA5, other gridded datasets, and observations to run the HMETS hydrologic model in many catchments across North America. Compared to their results for catchments of similar elevation and size to Bennett Creek and in the same region of North America, the Bennett Creek Ages model is performing better than at least the lower quartile of catchments in their study, even though this study conducted simulations using on a daily timestep. The Bennett Creek Ages model does overall exhibits somewhat lower statistical metrics than the Tarek et al (2020) study, but calibrating a model to a finer timescale is expected to be more challenging. Considering the increased difficulty presented with an hourly timestep, and the very limited data available at this time increment, the models' performance may actually be better than a daily or monthly model with similar statistical metrics. It is important to attempt a calibration at this scale if the model is to be used for peak flood estimation or scaled down to model processes at the subwatershed and hillslope scale.

3.1.3 Grouped Calibration Parameters & Hydrologic Processes Discussion

Table 3-4 contains the model-input parameters that were set to calibrate independently for HRU groups based on whether they were represented as burned or unburned along with their final calibrated values. Recall Table 2-1 that describes the acronyms for model input parameters representing various hydrologic processes. The various parameters in Table 3-4 relate to hydrologic processes represented in the model. Evapotranspiration processes were best represented in burned and unburned areas by differences in soil polynomial reduction (soilPolRed) and the soil layer evapotranspiration coefficient (BetaW). The amount of actual evapotranspiration compared to the potential evapotranspiration is controlled by soilPolRed, where a decrease in burned HRUs would lead to a relative decrease in ET. An increase in betaW in burned HRUs, on the other hand, means that the relationship between plant ET and root depth becomes less linear, where ET closer to the surface becomes greater than that at full root depth. These processes may be affected as a result of the loss of vegetation in burned areas, causing less ET and for remaining ET to be concentrated towards the surface due to root disruption.

Table 3-4 Subset calibration parameter results for burned and unburned HRUs. Range denotes the range over which the parameter was allowed to vary during calibration. Full descriptions of parameters and units are located in Table 2-1.

Parameter	Unburned	Burned	Range
soilPolRed	22	9.4	0.1-50
BetaW	3.2	6.5	0.1-15
soilMaxDPS	1.1	5.8	0-7
soilMaxInfSummer	120	58	0-250
soilDistMPSLPS	4.9	0.0	0-10
soilDiffMPSLPS	2.8	0.02	0.1-10
soilOutLPS	0.82	0.17	0.01-10
soilLatVertLPS	0.64	0.14	0.001-10
kdiff_layer	11	24	1-50
lagSurfaceRunoff	1.25	1.15	1-1.5

In the burned HRUs, a significant increase in simulated depression storage may be expected following wildfire and particularly at this site, where fallen tree trunks and excess debris can create areas for water to be stored and subsequently infiltrate. Generally, this result could also be interpreted as coming from either a hydrophilic ash layer, the presence of a mulch layer, or some combination of these, although mulch layers were not consistent at the site and distinct ash layers were not physically observed at this site at the time of the author's visit (18 months post-fire). Maximum infiltration rates in the summer may be reduced in burned areas because of the formation of hydrophobic layers near the soil surface and/or soil compaction. Once water infiltrates, it is divided by Ages into large pore storage and medium pore storage using the soil distribution to medium pore storage/large pore storage (soilDistMPSLPS) input field. A "small pore" storage is not conducted because small pores are assumed to hold residual water after drainage or wetting. The calibration drove the medium storage input parameter to zero in burned HRUs, suggesting that infiltration to medium pore storage is effectively prevented after the fire. Diffusion of water to medium pore storage from large pore storage is also severely limited as shown by the soil diffusion between medium pore storage and large pore storage (soilDiffMPSLPS) parameter being nearly zero for burned HRUs. The coefficient for outflow from large pore storage (soilOutLPS) is much lower for burned HRUs, meaning that water in large pore storage is allowed to dewater more rapidly, reaching the field capacity sooner. A low values for the lateral/vertical large pore storage coefficient (soilLatVertLPS) in burned HRUs means that almost all of the water that is allowed to flow out by soilOutLPS percolates downward to the next soil layer rather than out via interflow. These combined effects from calibrated soil model-input parameters suggests that interflow and evapotranspiration from soil layers are effectively eliminated for burned HRUs in the model. These processes may be limited due to infiltration dynamics causing most of water to leave an HRU via surface runoff or ET at the surface. This is consistent with wildfire-related impacts because of the formation of hydrophobic surface layers, lack of canopy coverage from plants, and lack of ET from plant roots at depth.

The Kdiff_layer parameter controls the model's representation of capillary flux between soil layers, acting as a resistance term, with smaller values allowing more flux. The increase in kdiff_layer in burned HRUs means that there is less capillary flux between soil layers in the medium pore storage, for the small amount of water that can reach soils in burned HRUs via infiltration (no water infiltrates to MPS in these HRUs due to soilDistMPSLPS = 0) or interflow from an adjacent unburned HRU.

Calibrated values for surface runoff lag (lagSurfaceRunoff) are similar for both HRU groups, but the slight decrease in lag time for burned HRUs may indicate that soil disturbance by fire creates less direct flowpaths across the land surface, in line with an increase in depression storage, requiring less lag adjustment from the model to satisfy flow volumes at the watershed outlet.

3.2 5-Minute Model Results

The analysis of hydrologic timing metrics focused on comparing observed and modeled precipitation-stage response lag times, time of concentration, and time to peak across the experimental subwatersheds. These comparisons aimed to evaluate the Bennett Creek 5-minute Ages model's performance in capturing flow timing and in identifying any differences in response characteristics between mulched and unmulched subwatersheds. Figure 3-5 shows the definition of time to peak, lag time, and time of concentration used in this analysis. All metrics were measured for both the observed and modeled timeseries, where lag time and time of concentration were measured using the aggregated and furthest upstream precipitation timeseries generated by the model's regionalization spatial adjustment.

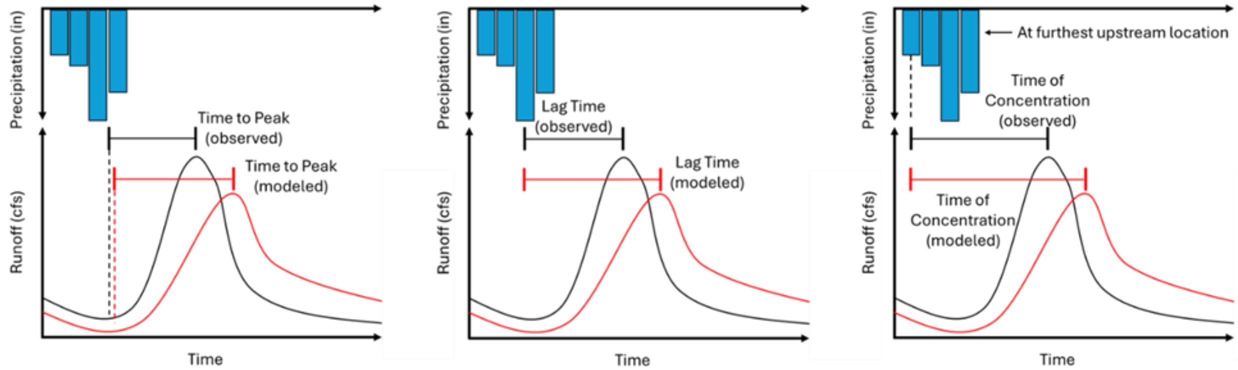


Figure 3-5 Example schematic hyetograph depicting time to peak, lag time, and time of concentration calculations.

Figure 3-6 (page 46) shows the results of the time to peak analysis. The coefficient of determination for all observations was 0.62, which is indicative of a weak-to-moderate correlation between time to peak for modeled vs observed events. A coefficient of determination of 1.0 on a trendline that equals y=x would indicate perfect estimation of runoff timing in the model, as compared to observations. In the grouped scatter plot, the coefficients of determination were 0.66 and 0.56 for mulched and unmulched conditions, respectively. Since the model was not constructed to represent mulched and unmulched subwatersheds differently, if a group's modeled time to peak is generally greater than observed time to peak (area above y=x in plot), it indicates that water movement is being modeled slower than reality for that group. The expected result for mulched vs unmulched subwatersheds is that more points representing mulched areas would underpredict time to peak, since in reality the mulch could slow down the flow of water through the catchment. The results do not clearly fall into separate groupings based on mulch treatment, contrary to expectations. For this reason, the time to peak data do not indicate a difference between mulched and unmulched subwatersheds.

Figure 3-7 (Page 46) shows the results of the lag time analysis. The coefficient of determination for all observations was 0.48, which is indicative of a weak correlation between lag times for modeled vs observed events. In the grouped scatter plot, the coefficients of determination were 0.53 and 0.47 for mulched and unmulched subwatersheds, respectively. Since the model was not constructed to represent mulched and unmulched subwatersheds differently, if a group's modeled lag time is generally greater than observed lag time (area above y=x in plot), it indicates that water movement is being modeled slower than reality for that group. The expected result for mulched vs unmulched subwatersheds is that more points representing mulched areas would be located in this section of the plot, underpredicting lag time, since in reality the mulch could slow down the flow of water through the catchment. In this case, the results plot into somewhat separate groupings based on mulch treatment with more mulched modeled lag times underpredicting the observed lag times at their respective location. For this reason, the lag time data indicate some amount of difference between mulched and unmulched subwatersheds, which can possibly be attributed to mulch application.

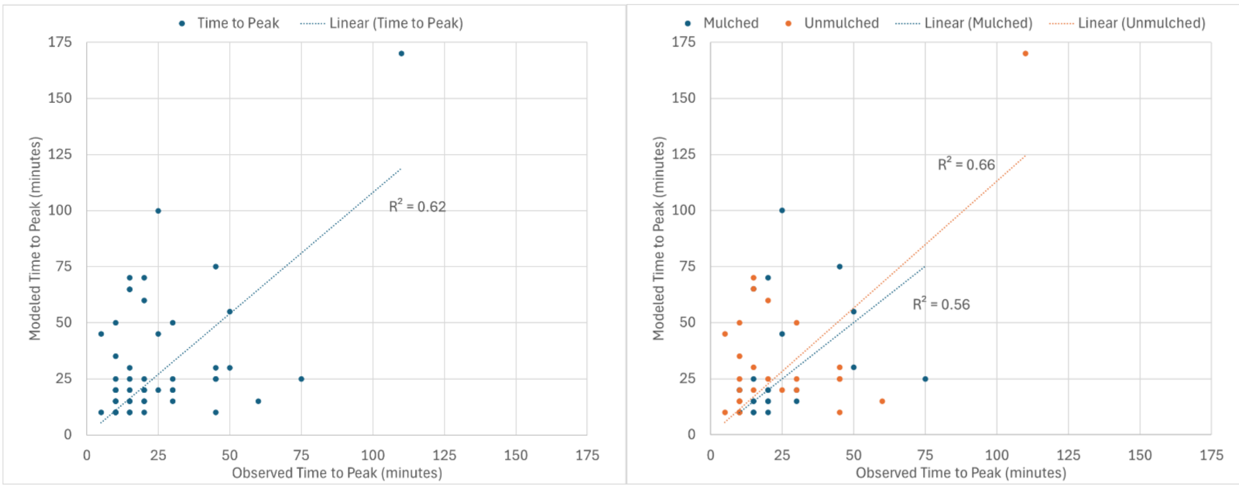


Figure 3-6 Observed vs. Modeled time to peak scatter plots with linear trendlines and coefficients of determination. The plot on the right is divided into data from Mulched and Unmulched experimental subwatersheds, with trendlines and coefficients of determination calculated separately for each group.

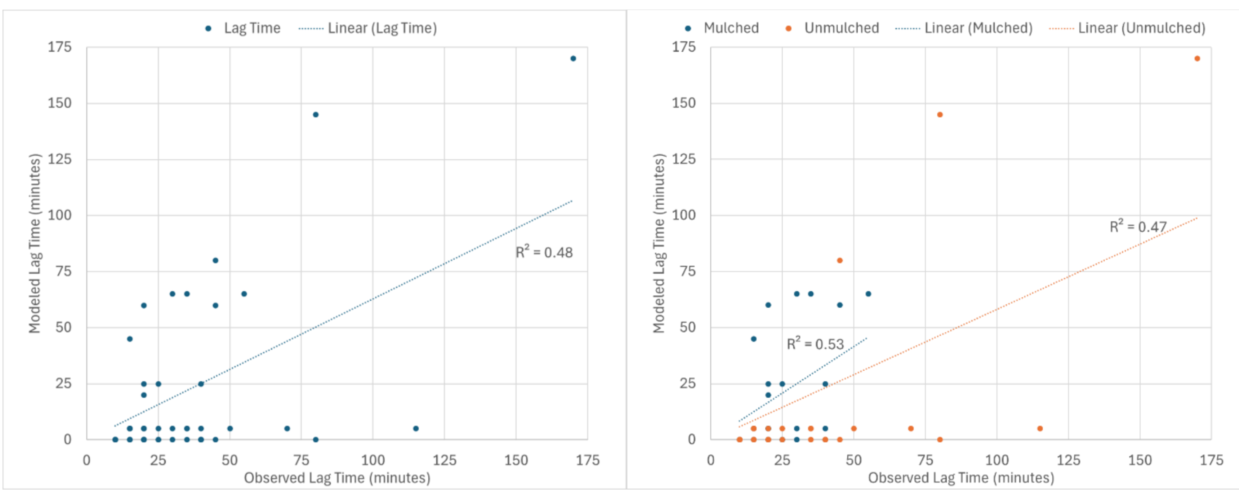


Figure 3-7 Observed vs. Modeled lag time scatter plots with linear trendlines and coefficients of determination. The plot on the right is divided into data from Mulched and Unmulched experimental subwatersheds, with trendlines and coefficients of determination calculated separately for each group.

Figure 3-8 (page 47) shows the results of the time of concentration analysis. The coefficient of determination for all observations was 0.89, which is indicative of a strong correlation between time of concentration for modeled vs observed events. In the grouped scatter plot, the coefficients of determination were 0.87 and 0.94 for mulched and unmulched subwatersheds, respectively. Because the model was not constructed to represent mulched and unmulched subwatersheds differently, if a group's modeled time of concentration is generally greater than observed time of concentration (area above y=x in plot), it indicates that water movement is being simulated slower than reality for that group. The expected result for mulched vs unmulched subwatersheds is that more points representing mulched areas would be located in this section of the plot, underpredicting time of concentration, since in reality the mulch could slow the flow of water through the catchment. In this case, the results plot into somewhat separate groupings based on mulch treatment with more mulched modeled lag times underpredicting the observed time of concentration at their respective location. For this reason, the time of concentration data indicate some amount of difference between mulched and unmulched subwatersheds, which can possibly be attributed to mulch application. This implies that the application of mulch has some observable effect in slowing the timing of flows at the subwatershed scale. If more mulch were to be applied (either in terms of spatial coverage or density of application) more of an effect would be expected. This gives some hope that mulching may be an effective treatment option in this setting.

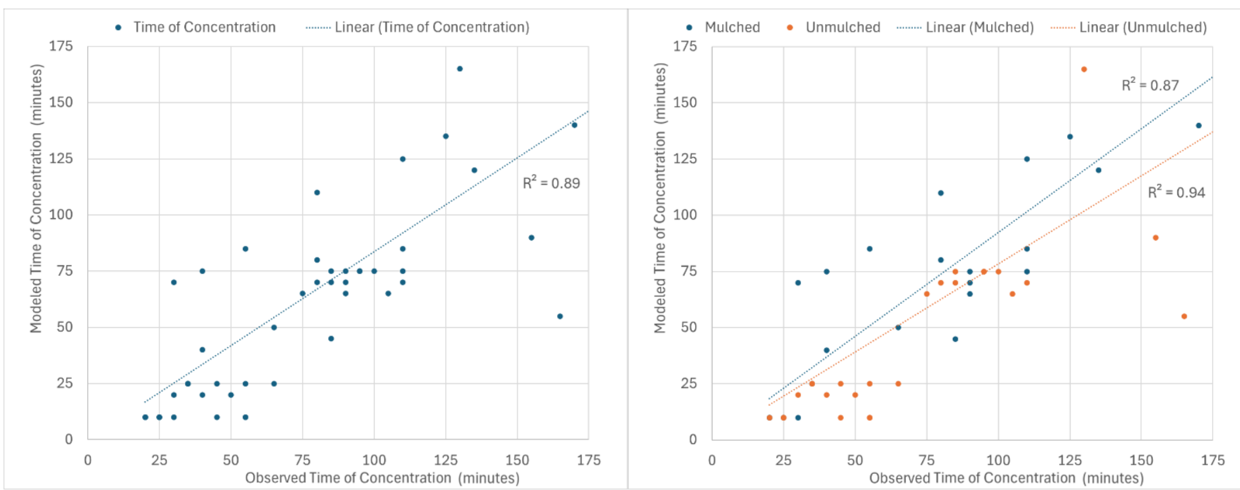


Figure 3-8 Observed vs. Modeled time of concentration scatter plots with linear trendlines and coefficients of determination. The plot on the right is divided into data from Mulched and Unmulched experimental subwatersheds, with trendlines and coefficients of determination calculated separately for each group.

3.3 Benefits, Uses, and Importance of Bennett Creek Ages Model

The Bennett Creek Ages model and the associated study provide significant advancements in model configuration, data usage, and understanding and managing hydrologic responses in post-fire watershed dynamics. This comprehensive modeling effort reveals substantial information about how wildfires alter hydrological processes, providing insights crucial for ecological restoration and risk management in affected watersheds. One of the primary benefits of this study is its deep dive into the behavior of hydrologic processes following wildfires, especially in terms of how these processes differ between burned and unburned hydrologic response units (HRUs). By modeling these distinctions, the study highlights the significant role that vegetation and soil properties play in mediating hydrologic responses post-fire.

A number of review articles have been published in recent years that highlight many research gaps in the fields of post-wildfire hydrologic processes and modeling, which this study has addressed. The review published on post wildfire runoff and erosion processes by Moody et al. (2013) identifies determining the best time-averaging interval to represent meso-scale rainfall and the runoff responses that result? It is acknowledged that this question depends to some degree on the spatial scale of focus. Their review identified 30 minute time intervals to align best with peak discharge. This study contributes to knowledge in this area by asserting that 1-hour intervals are sufficient for catchment-scale runoff, but shorter time intervals are necessary to simulate hillslope or HRU-scale processes. The review published by Basso et al. (2022) highlights the need for post-fire catchment scale models to represent ecosystem/vegetation recovery in tandem with slope connectivity and burned soil properties. This study contributes a model of this very configuration, where vegetation recovery is represented through adjustments to growth curves and LAI parameterization, slope connectivity is represented by the model's relatively small HRU size and fully distributed routing, and representation of burned soil properties via separately calibrated parameters based on burn severity. Ebel at al. (2023) published a review on future directions for applications of physically based distributed simulation for post-wildfire hydrologic response that proposes a number of additional research needs that are advanced by this study. By virtue of the architecture of the Ages model, the first major research area addressed in this study is the needs for representation of both unsaturated and saturated soil processes, as well as all four major runoff generation mechanisms: infiltration excess, saturation excess, subsurface storm flow, and groundwater flow. The Bennett Creek Ages model accomplishes all of these goals, because all of these processes are explicitly modeled. Similar to Basso et al., Ebel et al. stress the desire for a model that links vegetation regrowth with hydrologic processes. According to Ebel et al., this study is also unique in that not many post wildfire modeling studies use spatially distributed precipitation datasets, with less using gridded rainfall estimates, and even less using radar QPEs (2%), which are all desirable advances to be made. This study is also an outlier in that only a fraction of the studies analyzed used changes in the parameterization of vegetation (LAI and regrowth) to alter interception storage. The authors also pointed out that burn severity and land cover are not often used to calibrate or parameterize surface roughness. This study calibrated depression storage based on burn severity as a component of surface roughness. The review also discusses how high temporal resolutions are desired for models that utilize gridded datasets, because daily timesteps are insufficient for representing high intensity rainfall and flashy post-fire runoff events (Ebel et al., 2023).

Addressing the study's primary research questions has yielded several key insights: The MRMS dataset, adjusted to an hourly and 5-minute scale, has proven to be a reliable source of rainfall data for hydrologic modeling at Bennett Creek. This high-resolution dataset captures the spatial variability of rainfall essential for accurate modeling in the complex terrain of post-fire landscapes, where hydrologic responses can be highly localized and variable. Kinoshita et al. (2014) found in their comparison of various models in post-fire applications that distributed models performed better than lumped models, which this study corroborates since peak flow estimates were better than the majority of results from the 5 models featured by Kinoshita et al. (2014). Tarek et al. (2020) cite the need for evaluation of hydrologic model performance on a subdaily timescale using ERA5 data as a continuation of their work, which this study accomplishes by demonstrating that ERA5-Land data are sufficient for climate forcing in a physically-based, hourly-scale hydrologic model.

However, the model's ability to estimate peak flows accurately emerged as a limitation. It tends to overpredict initial runoff events following a fire and underpredict subsequent ones. This discrepancy indicates that while the model is highly effective for general hydrologic assessments and understanding the broader impacts of fire on watershed dynamics, it requires further refinement for applications that need precise peak flow predictions. Such precision is crucial for designing infrastructure and management practices aimed at flood prevention and water resource management in fire-affected areas.

The study successfully demonstrates that most important fire-impacted hydrologic processes can be represented using spatially distributed model parameterization. This approach allows for a detailed representation of varying hydrologic responses across different parts of the watershed, influenced by factors such as soil hydrophobicity and vegetation loss due to fire. This level of detail enhances the model's utility in planning and implementing post-fire recovery and mitigation strategies.

The potential of subhourly model simulations was also explored, showing promise for providing valuable insights into the timing of runoff events at a subwatershed scale. This finer temporal resolution is critical for understanding and managing fast-responding hydrologic systems, particularly in smaller, steep, or highly variable landscapes where hydrologic responses can occur rapidly following rainfall events.

Overall, the Bennett Creek Ages model stands as a critical tool in the toolkit of watershed managers and researchers. It offers a dynamic platform for simulating and understanding hydrologic responses in post-fire environments, providing a foundation for informed decision-making and effective watershed management. With further calibration and integration of real-time data, the model's accuracy and applicability are expected to enhance, making it even more indispensable for addressing the challenges of managing fire-impacted landscapes.

3.4 Recommended Areas of Future Research

While the current model developed for this research was useful in its current form, and is necessary for continued development and improvement of post-fire hydrologic modeling, continued work will enhance the model for other intended uses. The Bennett Creek Ages model's tiered HRU delineation with very small HRUs in the experimental catchments will allow for future investigation into hydrologic, sedimentation, and nutrient cycling dynamics at hillslope, subwatershed, and watershed scales. If better characterization of hydrologic conditions of the experimental catchment outlets is desired, one could explore the use of alternative gridded climate forcing data. A meteorological station has recently been installed at Bennett Creek along with an array of soil moisture sensors, which if used may improve future model performance. Using data from new meteorological stations within the watershed could to be used directly as forcing data or used to scale gridded climate data and could potentially provide more accurate model representation. Additionally, one might employ a 4-tier burn severity parameterization for unburned, low, medium, and high severity zones, rather than this study's binary burned/unburned at the classification. If hydrophilic ash layers are or were at some point present in the study area, representing them as a soil layer in the model may help disentangle some of the more nuanced effects it may have on rainfall-runoff thresholds. Another area of future research that could improve the Bennett Creek model's performance and potentially advance postfire modeling would be the construction of a feature that allows a user to program time-varying parameterization, as it would allow the user to mimic a watershed's recovery back towards its baseline conditions after a fire in addition to vegetation-related processes.

Stream water quality data that is being collected could be used to help calibrate the water quality components of the model, such as sediment transport and nitrogen cycling. These processes would be valuable to model as they both relate to the ecological health of a site following wildfire but would also help characterizes slope stability and landslide risk. The Bennett Creek Ages model is already equipped with HRUs within these experimental catchments that are smaller in size and would be useful in simulating processes on a hillslope or even plot scale with the smallest HRUs. The subhourly version of the model would be used in this case because the movement of water through small HRUs cannot be captured on an hourly scale. That is, the time of concentration for catchments this small is less than the resolution of a single hourly timestep. Ultimately, the hope is that future experimentation may be able to detect a difference between mulched and control catchments, as they were mostly unable to accomplish it so far, in which case the model could be parameterized for representation of a mulch layer and applied to problems dealing with the modeling and projected effects or benefits of mulch application. This may be aided by additional mulch application in the experimental subwatersheds. The addition of instrumentation at the experimental catchment sites for meteorological, precipitation, and flow observations across longer timespans will give the model more opportunity to calibrate with and improve its performance. These additional data could also be combined with remotely-sensed gridded products like those used in this study to combine the strengths of the spatial distribution of gridded data and the realism of data from on-site instrumentation.

Some of the main limitations of this study were the seasonality of gage records, lack of gage records pre-fire, lack of the ability to model parameters gradually changing over time, lack of a control gage in an unburned catchment within the study area, and any inaccuracies present within the climate or precipitation data. Based on how the model performed, it should not be used in situations where precise peak flow estimation is desired, because it does not seem to be reliably able to do so. Model outputs for the first season post-fire overpredict the first rainfall-runoff event and underpredict the rest – this may indicate that a crucial dynamic involving surface storage in ash and/or hydrophobicity in crust layers (as proposed in Basso et al., 2022 and Moody et al., 2009), revegetation of burned areas, or some other unknown process is being represented poorly. For this reason, along with the model's inability to alter parameters on a daily or even monthly scale, it is not recommended to be applied in modeling recovery dynamics of the watershed, unless more time and care is taken to perform calibrations on each year of data, or to determine a method for time-varying parameterization.

CHAPTER 4 CONCLUSIONS

The Bennett Creek Ages model, through detailed hourly calibration, has demonstrated proficiency in capturing the dynamic hydrologic processes in a post-wildfire setting within the Colorado mountains, with the exception of peak flow. This model's ability to reflect observed data at the catchment outlet and align with the results from similar studies underlines its robustness and adaptability to the nuanced environmental shifts following wildfire events. However, the study also acknowledges several limitations that underline the need for continued refinement and expansion of the model's capabilities, or collection of additional data. In particular, simulation of peak flow needs to be improved.

This study's in-depth examination reveals the critical role of vegetation in moderating watershed hydrology, with burned HRUs showcasing increased surface runoff due to reduced interception and transpiration capabilities post-fire. The model handled these variations, where adjustments to soil hydraulic properties were crucial for enhancing its prediction accuracy. These modifications have not only improved the model's output but also highlighted the essential ecosystem services provided by intact forest areas, which stabilize the hydrologic cycle and reduce the risk of erosion and flooding post-disturbance.

The calibration process itself was a testament to the model's capability to adapt to the altered physical properties of the soil post-fire, particularly in terms of reduced infiltration rates and modified water storage capacity. Use of a limited flow record for calibration of the model to reasonable standards is a success in itself, and a contribution towards the knowledge of what is possible in terms of post fire modeling in poorly instrumented catchments.

The Bennett Creek Ages model was constructed with a flexible architecture that supports ongoing research and adaptation, including investigations into mulching treatments, nutrient cycling, and varied input scenarios, which are essential for managing complex mountain hydrology post-wildfire. The ability of this model to operate at timesteps as short as 5 minutes (or shorter) provides a useful tool for modeling the timing of flows and peak flows across different watershed locations, demonstrating its applicability to remote, poorly instrumented catchments. Both subdaily configurations of the model are uncommon in post-wildfire modeling and represents an important first step toward simulating post-fire hydrologic responses at the appropriate temporal scale.

Future research should focus on leveraging newly installed meteorological stations and soil moisture sensors at Bennett Creek, which are anticipated to enhance the model's input data quality and, subsequently, its predictive accuracy. The integration of these on-site data sources could potentially refine the model's representation of climate forcing, which has been a critical aspect given the variability in post-fire recovery dynamics.

Incorporating stream water quality data into the model could enable a more comprehensive analysis that includes sediment transport and nutrient cycling, essential for assessing ecological health and slope stability post-wildfire. The model's challenges with accurate peak flow estimation indicate that further calibration, possibly through subhourly simulations, is necessary to improve its utility in detailed flood risk assessment and recovery dynamics modeling.

The addition of finer scale HRU delineation allows for a more granular investigation of hydrologic processes, which could improve our understanding of the effects of mulching treatments on hydrologic recovery, an area that has yet to yield significant insights. This points to a broader need for the model to accommodate time-varying parameterization, allowing it to adapt to gradual ecological changes over time rather than remaining static.

The model's performance in the Bennett Creek study illustrates its potential as a helpful tool for studying post-fire rehabilitation treatments, not just in the Cameron Peak burn scar but in similar environments globally. This ability to model hydrologic responses with such detailed temporal resolution is crucial for developing adaptive management strategies aimed at mitigating the hydrologic extremes associated with wildfire events, thereby contributing significantly to the field of hydrologic science in both theory and applied practices in post-fire recovery and ecological restoration.

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APPENDIX A PERMISSIONS

Randy Wade (Student)

From: Green, Tim - REE-ARS <tim.green@usda.gov>
Sent: Thursday, January 2, 2025 12:06 PM
To: Randy Wade (Student)
Subject: [EXTERNAL] RE: [External Email]request for reproduction of copyrighted material

CAUTION: This email originated from outside of the Colorado School of Mines organization. Do not click on links or open attachments unless you recognize the sender and know the content is safe.

Hi Randy,

Yes, you can use that or any other figure. It's good to know that you are wrapping up the MS thesis. I'll read you thesis draft before Monday.

What time is the defense? May I share the meeting link with others like Rob, Holm and Nathan?

Thanks,
Tim

From: Randy Wade (Student) <rwade@mines.edu>
Sent: Thursday, January 2, 2025 6:38 AM
To: Green, Tim - REE-ARS <tim.green@usda.gov>
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If this message comes from an **unexpected sender** or references a **vague/unexpected topic;**
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Hello Tim,

I was wondering if it would be alright to use a graphic from one of your papers in my thesis. The one that I am interested in using is Figure 2 from "The AgroEcoSystem (AgES) Response-Function Model Simulates Layered Soil-Water Dynamics in Semiarid Colorado: Sensitivity and Calibration"? I have attached an image of this figure for reference.

Thank you,

Randy Wade
Graduate Student
Hydrologic Science & Engineering
Colorado School of Mines
E: rwade@mines.edu
COLORADOSCHOOLOFMINES
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Figure 4-1 Permission from author of *The AgroEcoSystem (AgES) Response-Function Model Simulates Layered Soil Water Dynamics in Semiarid Colorado: Sensitivity and Calibraiton* (Tim Green) for the reproduction of Figure 2-7.