FINAL REPORT

Effects of Wildfires and Fuel Treatment Strategies on Watershed Water Quantity across the Contiguous United States

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ABSTRACT

Forest watersheds provide over half of our national water supplies. Millions of people depend on surface freshwater supplies from fire-prone headwater forests, used for drinking, irrigation, industry, and hydropower. However wildland fires in the contiguous United States (CONUS) have increased in frequency, size, and severity, giving rise to concerns about the sustainability of clean, reliable supplies of surface freshwater. While wildfire seasons become longer, much remains unclear about the connection between wildland fire characteristics, drought, and water supplies at the national scale. The goal of this study is to generate new practical knowledge useful for decision making in minimizing wildfire impacts on water quantity and quality and enhancing watershed ecosystem resilience across the CONUS. This study focuses primarily on water quantity at a spatial scale of medium to large watersheds (>22, 000 acres or 90 km^2), approximately the size of HUC-12 watersheds. We developed a framework for evaluating wildland fire impacts on streamflow that combines double-mass analysis with new methods (change point analysis, climate elasticity modeling, and process-based modeling) to distinguish between multiyear fire and climate impacts. The framework captures a wide range of fire types, watersheds characteristics, and climate conditions using streamflow data, as opposed to other approaches requiring paired watersheds. We combined river flow, climate, and wildland fire data of the past 30 years for 168 burned watersheds in the CONUS, and performed an in-depth assessment of the coupled wildland fire-surface water supply risk in 32 locations, where stream gauges were located close to the fire. These 32 locations were situated within the Osceola National Forest (NF) and Apalachicola NF in Florida, De Soto NF in Mississippi, Gila NF, Tonto NF, and Coronado NF in Arizona, Uinta NF in Utah, Okanogan NF in Washington, Sawtooth NF, Boise NF, and Payette NF in Idaho, Siskiyou NF in Oregon, and Cleveland NF, Los Padres NF, Stanislaus NF, Lassen NF, Mendocino NF, and Klamath NF in California. This study indicates that wildfire enhanced river flow amid droughts in the Lower Colorado and Pacific Northwest regions relative to the river flow expected had the fire not occurred. However, the flow enhancement in Southern California was masked by drought. Data for the 168 burned watersheds in the CONUS show that the rule of thumb stating that at least 20% of the basal area must be removed, in order to produce any significant change in river flow, also applies to the area affected by wildland fire. In addition, areas affected by low burn severity had no appreciable, direct effect on river flow. As a result, prescribed burns did not significantly alter river flow in the Southeast U.S. in basins larger than 10 km^2, because the area affected by the burn was typically too small (<20%), and characterized by low burn severity. We conclude that river flow after wildland fire was primarily driven by climate, with seasonal variations in precipitation playing the most dominant role in the West. Among secondary factors, wildfires with moderate to high severity burn impacts, and topography had the greatest impact on the post-fire change in river flow in the West. Land cover, and in particular the amount of barren land and urban extent, was a secondary predictor in the East. The large regional variability of river flow responses to wildland fire has major implications for floods mitigation, watershed restoration, and for forest management policies aimed at reducing wildland fire risk and improving water supply under a changing climate. Land management options such as prescribed burning and forest thinning to reduce fuel loads and maximize ecological benefits (i.e., water yield) must be developed to fit local conditions (i.e., climate, watershed size, and topography). Future studies are needed to examine response of ecohydrologic processes to wildland fires across multiple gradients including climate and topography to further understand and predict wildfire impacts on watersheds.

OBJECTIVES

The original three major specific objectives for this study are: 1) to combine historic large wildfire and USGS streamflow records to examine hydrologic impacts of past large wildfires and validate process-based models for regional applications, 2) to evaluate the sensitivity of watershed seasonal water yield to fuel management strategies at the basin scale (12 digit Hydrologic Unit Code) across the CONUS using a regional water balance model, and 3) to identify key municipal watersheds that are most vulnerable to wildfires and to quantify potential short and long-term impacts of wildfires on water supply and peak flow rates using a process-based hydrologic model. Our five original guiding hypotheses listed below focus on regional differences of hydrological responses to disturbances that vary with fire characteristics (fire severity and burn areas) under different climatic regimes (dry vs wet climate) (fig. 1).

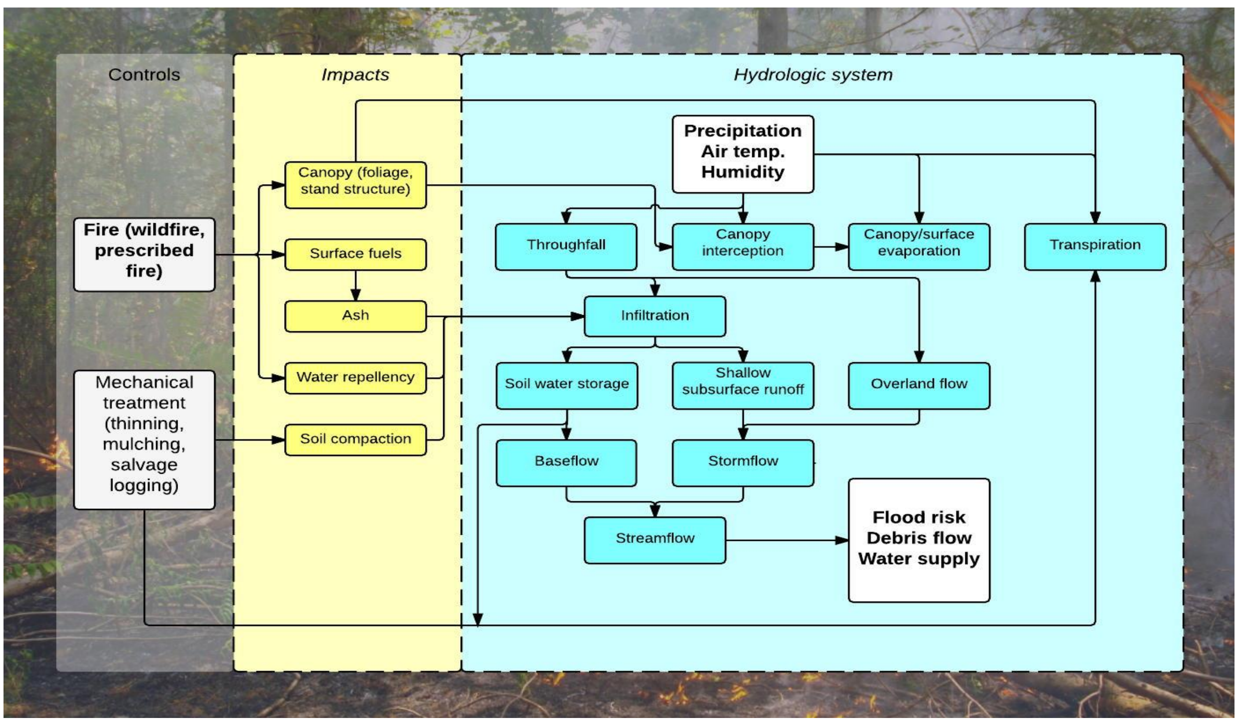


Figure 1. A conceptual model describing the impacts of wildfire on watershed hydrology.

Overall, we have confirmed all hypotheses in term of the large variability found. However, we did find surprises about hydrological responses in certain watersheds that could not explained by our models and data.

H1: Regionally, wildfires have higher impacts on total water yield volume in wetter regions (e.g., southeastern U.S., coastal regions) or wetter years than drier regions (interior West) or years. The drier regions with low streamflow are expected to have higher response in relative terms (percentage change in streamflow and peakflow rates). The most sensitive regions for percentage change in water yield are those areas where annual precipitation is close to potential evapotranspiration.

H2: Under a particular climate regime, hydrologic responses such as water yield, stormflow volume, and peak flow rates increase with fire severity, fuel treatment intensity (acreage treated, and soil and vegetation disturbance level), and decrease with the time interval between the burns and the next rainfall events. Change in Leaf Areas Index (LAI) or Basal Area (BA) can be used as effective surrogates for fire severity and fuel treatments that directly link watershed biophysical conditions to hydrologic response.

H3: The hydrologic responses to wildfires in any watershed become detectable/significant only when the area of forest vegetation burned, removed, or thinned exceeds 20-40% of the total area depending on climatic characteristics (i.e., snow vs rainfall dominated systems). The spatial locations of the burn areas in a watershed influence this threshold.

H4: Watershed hydrology affected by wildfires in a drier climate (e.g., interior West) takes longer time to recover than in a wetter climate (e.g., southeast, coastal regions) due to the slower vegetation regrowth rate and recovery of ecosystem evapotranspiration in the West.

H5: Significant increases of large peakflows that trigger debris flow and flooding after severe wildfires are a result of soil disturbances (e.g., loss of woody debris, soil compaction) that cause a large reduction in infiltration, not necessarily due to vegetation loss.

INTRODUCTION

Water, Wildland Fire, and People

Water supplies in the United States are experiencing stress from more frequent and severe droughts accompanied by extreme wildfires (Dennison and others 2014). These fires consume forest canopies and can cause extensive property damage. Severe wildfires produce a cascade of indirect hazards triggered by rainstorms, such as floods, excessive erosion, and debris flows (Cannon and others 2011, Elliott and Parker 2001, Littell and others 2016, Moody and others 2001, Neary and others 2005, Shakesby and Doerr 2006, Williams and others 2014). Large and severe fires also affect the amount and quality of water supplied by rivers, sometimes over the course of years (Hallema and others 2018a, Rhoades and others 2018). Consequently, fires not only affect the people living near forests (Radeloff and others 2018), but also those living outside the immediate range of these fires.

Post-fire threats cause uncertainty about the amount and quality of surface water, and increase the cost of water treatment and flood mitigation (Bladon and others 2014, Martin 2016). The effect of any particular fire on surface water is often difficult to detect over a longer time frame given due to a variety of confounding factors. Some of these factors pertain to the inter-annual variability in climate and evapotranspiration (Hallema and others 2017a), and others are related to the complexity of landscape interactions and the time it takes for water to move through the basin (Hallema and others 2017b). Fire effects on surface water further depend on the extent and severity of a fire (Hallema and others 2018a).

Natural wildfires and most prescribed burns (Figure 1) are vital to the ecological succession of forests, savannas, and prairies, and provide significant ecosystem benefits (Lafon and others 2017). They consume built-up fuels from dead vegetation and make room for new growth. Numerous plant species even depend on fire to germinate and thrive—the benefits of fire to biodiversity and forest health are widely recognized. Many forests, however, have developed a high density of vegetation after decades of fire suppression, which acts as fuel for wildfires. The combination of more fuels and increasing drought occurrence is causing more severe, more devastating wildfires (Westerling and others 2006), leading to increased surface water yield from headwater catchments in the years after wildfire (Hallema and others 2018a).

Increased post-fire surface water yield are both good news and bad news. They can relieve water stress if the water can be used for irrigation and other purposes. But oftentimes, wildfires also cause floods (Cannon and others 2008), increase stream temperatures (Koontz and others 2018), and degrade the water quality (Rust and others 2018). This has a negative impact on aquatic ecosystem health and increases the treatment cost to ensure compliance with standards based on the Clean Water Act. Areas in the wildland-urban interface and downstream urban areas using surface water from forest catchments are particularly sensitive to this trade-off (Sun and others 2017, Sun and others 2018).

The dependence on forest water supplies indicates that wildland fire effects on surface water yield can potentially impact the safety and economic welfare of a large portion of the U.S. population. Forests provide an array of hydrologic services (Keleş 2018): public and private forests provide approximately 50% of the surface freshwater supply in the Western states (Brown and others 2008), and in the Southern states, forests deliver up to 35% of consumed water (Caldwell and others 2014). National Forests play a vital role in water production, accounting for as much as 18% of the total U.S. freshwater supply (Caldwell and others 2014, Cohen and others 2017). A major issue for example is that increased post-fire sediment yield contributes to more rapid filling of reservoirs, with implications not only for surface water storage, but also for hydropower and flood hazard mitigation (Murphy and others 2018).

Fires Are Part of the Landscape

Fires are part of the landscape, but every fire is different. Wildfires can occur naturally, when sparked by lightning, or are caused by humans. How often they occur, in other words the fire frequency, depends on temperature and precipitation patterns (fig. 2), steepness of the terrain, and slope aspect (Touchan and others 1996). The combination of fire characteristics and their effects on ecosystems define a fire regime (Agee 1993), and are measured in terms of fire extent, spread pattern, intensity, severity, depth of burn, recurrence interval, and season (Neary and others 2005). Topography is often a good predictor of severe fire occurrence at high elevations because north-facing slopes tend to be cooler and wetter, and accumulate more biomass than south-facing slopes (Dillon and others 2011).

Prior to widespread fire exclusion, many Western ecosystems experienced frequent low-intensity understory fires and occasional stand-replacing fires (Swetnam and Baisan 1996). The western slopes of the Cascade Range in the Pacific Northwest, for example, which receive a large amount of precipitation, experienced severe wildfire every 26 to 100 years (Frost 1998). Wildfire was more frequent in the Sierra Nevada and the Rocky Mountains, where annual precipitation was less and fire returned every 13 to 25 years (Frost 1998). In drier landscapes, like the coniferous forests east of the Cascade Range, fire returned every 11 to 21 years (Johnston and others 2017), and in Southwestern ponderosa pine and mixed evergreen forests, every 5 to 22 years (Allen 1989, Swetnam and others 1989, Touchan and others 1996, Weaver 1951).

In the Eastern part of the continent, forest wildfire patterns were very different. Wildfires returned only once a century in the humid Northern Appalachians, most of the Great Lakes region and in the Northeast Interior (Pennsylvania, New York, and New England) (Frost 1998), but every 6 to 13 years in the Southern Appalachians (Flatley and others 2013). Owing to low relief in the wetlands of the Southeast coastal plain, this region experienced intense brush fires as frequently as every 2 years (Frost 2000).

Although wildfires have been part of the natural landscape since the first forests appeared, fire behavior and fire threats to humans have changed in response to climate trends and increased human presence. Fire suppression was introduced to protect lives and property, and with the intention to preserve forests for timber harvesting. Fire suppression became commonplace in the West by the 1930s, and in the East by the 1940s. In the absence of fire activity and large scale clear-cut logging in the East, fuels were allowed to build up over time, with the unintended effect of increasing the number of severe fires over time (Lafon and others 2017). This increase is characteristic of the ecological frontier, where fires are sparked by both natural and human ignition sources (Robinne and others 2016a).

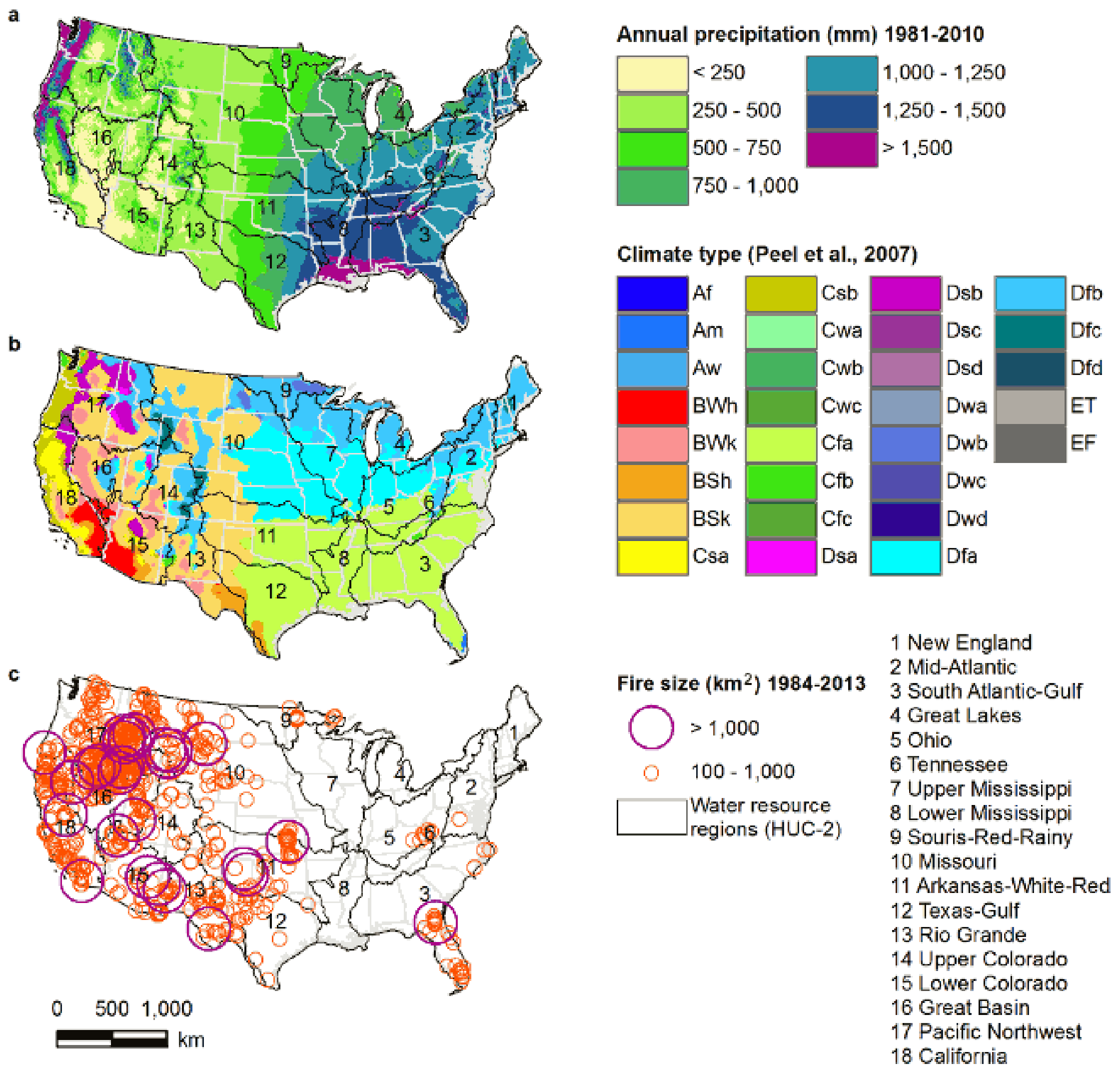


Figure 2. (a) Mean annual precipitation in the contiguous United States (CONUS) between 1981 and 2010 (PRISM data; Daly and others 1994, 2004); (b) climate type according to the Köppen classification (Peel and others 2007; key provided in Appendix A); and (c) location and size of the largest wildland fires observed between 1984 and 2013, concentrated in less inhabited locations (Monitoring Trends in Burn Severity; Eidenshink and others 2007). Water resource regions are numbered 1-18 and correspond with HUC-2 scale basins (USGS).

Regional Trends in Wildland Fires

The average burned area and burn severity for the contiguous United States as a whole have not changed substantially in the past three decades (Lin and others 2014, Picotte and others 2016), but locally fire activity has increased in response to complex interactions between climate, human presence, species composition, vegetation density and fuel build-up (Lin and others 2014). Between 2001 and 2010, the annual number of large wildfires increased in the northcentral (8.4%), northeast (10.8%), southcentral (7.3%) and southeast (16.5%) parts of the country, and decreased (3.6%) in the Rocky Mountain region (Lin and others 2014).

In the Western U.S., the Sierra Nevada and Southern Cascade Mountains experienced an increase in large fires between 1984 and 2006 (Miller and others 2009). There was no trend in the percentage of high-severity fires between 1987 and 2008 in Northwestern California, but in years with region-wide lightning activity the percentage of high-severity fires was smaller, while the burned area was larger (Miller and others 2012). Burned area and burn severity increased between 1984 and 2006 in the Southern Rockies, Mogollon Rim and the Colorado Plateau (Dillon and others 2011). But no significant trends were observed in the Pacific Northwest and Northern Rockies (Dillon and others 2011).

Fire trends evolved differently in the Eastern U.S. Large-scale reforestation of abandoned agricultural land in the past century (Pan and others 2011) shifted successional trends toward those observed in older mesic closed-canopy forests (Abrams 2003, Little 1979). These trends reduced the flammability of understory and litter fuels (Kreye and others 2013), resulting in smaller wildfires and lower fire severity compared to the historic regimes peaking around 1900 (Brose and others 2013, Little 1979). The large-scale conversion of open savanna landscapes and prairies to closed mesic forests—*i.e.*, mesophication—of Eastern forests, is attributed to a combination of increased fire suppression after that time (Nowacki and Abrams 2008) and climate change (Pederson and others 2015).

Today, prescribed burns account for as much as two thirds to three-fourths of the area burned in the East (Clark and others 2014, Mitchell and others 2014). This is because trends in forest regeneration, forest fragmentation, land use, fire suppression and fuels management, reduce the occurrence of naturally caused wildfires (Clark and others 2014). Annual burned area may continue to grow in the near future under increasing temperatures and increasing frequency and severity of droughts, especially in Western regions (Keane and Loehman 2012). While fuels drive changes in fire frequency and severity, the limiting factor is often climate and the recurrence time of fuel-desiccating drought (Schoennagel and others 2004, Schoennagel and others 2011). Geographic patterns in burn severity are linked to topography, climate and lightning trends, and forest densification. This combination heightens the sensitivity of water supplies to impacts of post-fire hydrologic disturbance (Hallema and others 2018a, Yung and others 2009).

Burned Forests Affect Water Supplies

The combination of longer wildfire seasons, more fuels, and more human ignitions, increases the ecological and economic cost of fires in the U.S. (Balch and others 2017, Syphard and others 2017). Part of this cost is due to wildfire-related impacts on water supply (Bladon 2018, Doerr and Santín 2016, Emelko and others 2011, Jones and others 2017, Martin 2016, Ozment and others 2016). The quantitative impacts of individual wildfires vs. prescribed fires are not well known, and as such there is a critical need to assess how various wildland fire types affect water supplies (Bladon 2018, Hallema and others 2018b, Robinne and others 2018a)—and to integrate these effects into pyrogeography frameworks used to evaluate fire patterns and impacts (Bowman and others 2013, Krawchuk and Moritz 2014, Martin 2016, Mirus and others 2018, Robinne and others 2016b).

These fire impacts are themselves influenced by interconnected environmental and hydrological mechanisms (Robinne and others 2018b). For example, fire-induced loss of vegetation decreases interception by the forest canopy (Williams and others 2014) and decreases plant transpiration (Cardenas and Kanarek 2014, Kinoshita and Hogue 2011, Kinoshita and Hogue 2015). The postfire change in evapotranspiration therefore varies by vegetation type and burn severity. Evapotranspiration can decline by as much as 350 mm for high burn severity areas characteristics of wildfires (New Mexico, Poon and Kinoshita 2018). Closer to the ground, hotspots can also cause damage to soils, and reduce the ability of soil to absorb precipitation (Neary and others 2005).

These mechanisms have an immediate impact on the local water balance when affected by fire. The excess portion of water not absorbed by the soil during a rainstorm, flows downhill (Bart 2016, Moody and others 2009). Once this surface runoff reaches a river, water levels can increase rapidly (Kinoshita and Hogue 2015, Wagenbrenner 2013, Wohlgemuth 2016). This can lead to increased stream erosion (Florsheim and others 2017, Jung and others 2009) and elevated particulate matter concentrations in the years after wildfire (Rust and others 2018). In many cases, even moderate storms can trigger floods and debris flows in the years following the wildfire, due to the compound effects of changes in infiltration, snowpack, and evapotranspiration (Cannon and others 2008).

The likelihood of increased river flow and elevated flood risk is often highest in the months immediately following wildfire (Bart 2016), especially in arid watersheds with shallow soil depth (Buma and Livneh 2017). However, over a period of years, fires can change the forest structure (Ohana-Levi and others 2017) and lead to forest densification (Nowacki and Abrams 2008). These denser forests consume more water, and the effect on water supplies can last for many years (Martin 2016).

The discovery of lasting effects on surface water supplies is further supported by evidence of increased runoff in New Mexico (Wine and Cadol 2016), Colorado (Ebel and others 2016), Arizona and California (Kinoshita and Hogue 2015, Hallema and others 2017a). Some have suggested that Eastern forests can be actively managed to increase available water supplies, by combining low basal area of forest vegetation with prescribed burning (McLaughlin and others 2013). This raises the question: How widespread are wildland fire impacts on water supplied by rivers? And do such effects persist in the years following a fire?

The answer is a complex one, because the sum of effects and interactions between factors contributing to change in river flow are, at any given time, defined by time, space, and state of each factor (McNulty and others 2018). Patterns and trends in river flow are extremely variable between and within regions depending on interactions between wildland fire, vegetation cover and species, soil type and topography, and climate (Caldwell and others 2016, Luce and Holden 2009, Luce and others 2013, Moody and others 2013, Rice and others 2015). The amount of storm runoff reaching a river furthermore depends on the relative contributions from surface runoff and subsurface stormflow (Mirus and Logue 2013), the connection with upstream areas (Gumiere and others 2013, Hallema and Moussa 2014, Hallema and others 2016b), and the velocity of surface runoff flow (Hallema and others 2013, Rousseau and others 2013).

In this report, we disentangled these complex interactions and performed the first assessment of the wildland fire effects on surface water yield across all physiographic regions of the contiguous United States (CONUS). This assessment is the main outcome of Joint Fire Science Program 14-1-06-18 (Hallema and others 2016a, 2017a, 2017b, 2018a), here illustrated in more detail and with new results. First, we characterized gauged river basins affected by wildfires over the past 30 years using high-resolution data describing wildland fire characteristics, climate, river flow, topography and land cover. The river basins varied between 10 and 100,000 km^2 in area and experienced wildland fire types ranging from prescribed burns to extreme fire events.

We then entered the basin-scale data into a machine learning program we developed to account for local wildland fire-climate-environment interactions, and determine and the net impact of wildland fire on annual river flow. Finally, we integrated this information into the WaSSI distributed hydrological model to estimate the potential fire risk to water supplies for all CONUS watersheds. In combining national scale empirical data with computational modeling, we offer a new holistic perspective on the potential role of wildfire and prescribed fire in the management of surface water resources.

METHODS

Collecting the Data

We combined high-resolution CONUS data sets to characterize wildland fire, climate, topography, land cover, and river flow (table 1) (Hallema and others 2018a). First, we collected wildland fire locations, dates, extent and burn severity for the past 30 years from the Monitoring Trends in Burn Severity (MTBS) data set (Eidenshink and others 2007, Key and Benson 2006). We understand burn severity to a qualitative assessment of how a specific area has been changed or disrupted by fire (Eidenshink and others 2007, NWCG 2018). According to this definition, burn severity is the product of fire intensity, which is related to the energy released during the fire (Keeley 2009), and the residence time of the fire. It combines first and second order effects, including changes to dead and living biomass, soil exposure to heat, and fire byproducts like scorch, ash, and char (Eidenschink 2007).

MTBS distinguishes between unburned or underburned, low severity, moderate severity, and high severity burn impacts, and increased greenness. MTBS has been used for management purposes (Kolden and others 2015), and for studying burn severity and burned area trends (Dennison and others 2014, Picotte and others 2016), and forest disturbance (Hart and others 2015, Meng and others 2014). More recently, MTBS is also used to investigate secondary impacts of wildland fires, such as those relating to water supply and water quality (Hallema and others 2017a, Hallema and others 2018a, Rust and others 2018).

Next, we obtained the watershed boundaries of reference watersheds in the GAGES-II (Geospatial Attributes of Gages for Evaluating Streamflow, version II) dataset (USGS 2011, USGS 2015), and retrieved corresponding daily Daymet gridded climate data (Thornton and others 2014) and monthly Parameter-elevation Regressions on Independent Slopes Model (PRISM) gridded climate data (Daly and others 1994, 2004). Finally, we extracted land cover data from the 2001 National Land Cover Database (NLCD; Homer and others 2015), and topographic information from the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) (Danielson and Gesch 2011). This diverse assortment of data types allowed for a comprehensive characterization of factors that influence annual river flow.

Table 1. High-resolution spatial datasets and time series data used to determine wildland fire impacts on river flow (adapted from Hallema and others 2018a).

Dataset	Data Type	Spatial Format	Time Period	Date	Online Reference
MTBS Burned Area Boundaries	Fire attributes	Vector	1984–2014 Annual	9/25/2014	http://www.mtbs.gov
MTBS Burn Severity Mosaic	Burn severity	Raster 30 × 30 m	1984–2014 Annual	9/25/2014	http://www.mtbs.gov
Daymet v3	Climate	Raster 1 × 1 km	1980–2014 Daily	9/30/2016	https://doi.org/10.3334/ORNLDAAC/1328
PRISM	Climate	Raster 4 × 4 km	1980–2014 Monthly	2013	http://www.prism.oregonstate.edu
GAGES-II	River flow	(Time series)	1980–2014 Daily	2016	https://doi.org/10.5066/F7P55KJN
GAGES-II Geospatial attributes	Watershed boundaries	Vector	2011	2016	https://doi.org/10.5066/F7P55KJN
WBD Watershed Boundary Dataset	HUC-2 Water resource regions	Vector	-	2015	https://data.nal.usda.gov/dataset/watershed-boundary-dataset-wbd
GMTED2010	Elevation	Raster 244 × 244 m	2010	2010	https://lta.cr.usgs.gov/GMTED2010
NLCD 2001	Land cover	Raster 30 × 30 m	2001	2011	http://www.mrlc.gov/nlcd2011.php

Abbreviations: GMTED, Global Multi-resolution Terrain Elevation Data; MTBS, Monitoring Trends in Burn Severity; NLCD, National Land Cover Database; PRISM, Parameter-elevation Regressions on Independent Slopes Model.

Characterizing Burned Watersheds

We identified a plenary set of burned watersheds based on burn characteristics and availability of river flow data, in a stepwise approach (fig. 3) (Hallema and others 2018a). First, we selected the GAGES-II watersheds with a drainage area greater than 10 km^2, approximately the size of a headwater catchment, and a flow record spanning at least 2 decades. In addition, we only select watersheds with minimal human disturbances or hydrologic infrastructure (*e.g.*, dam, flow diversions, etc.) so that the effect of the burn on flow could be isolated from other factors. Then, we combined the GAGES-II watershed boundaries with the annual MTBS burn severity data, resulting in a dataset with information on burn severity for each 120 m × 120 m subdivision of the burned watersheds: ordinal classes of underburned or unburned, low, moderate, and high severity. Finally, we determined the fraction of the watershed burned for each burn severity class and for all classes combined. We call this the burned area ratio (BAR).

The resulting plenary set contained 168 burned watersheds with a BAR ≥ 1% for any degree of burn impacts in any single year between 1984 and 2008. By including small fires in the plenary set, we could calculate the respective influences of wildland fire size and severity, river system, climate, topography, and land cover on river flow. Secondly, we were able to establish the minimum BAR above which river flow is affected—the burned area ratio threshold (BAR_t). If watersheds experienced multiple wildland fires during the studied period, we selected the year with the highest BAR.

After identifying the plenary set of burned watersheds, we retrieved the corresponding fire dates and summarized data for river flow Q, precipitation P, and amount of water contained within the snowpack SWE. Monthly potential evapotranspiration (PET) was estimated from PRISM gridded climate data with Hamon’s method (Hamon 1961, Sun and others 2011). Finally, we determined for each burned watershed the NLCD land cover and GMTED2010 topographic characteristics such as elevation, slope, and aspect. We also calculated the watershed shape parameter describing the ratio of watershed perimeter to drainage area (Gravelius’ compactness factor; Gravelius 1914).

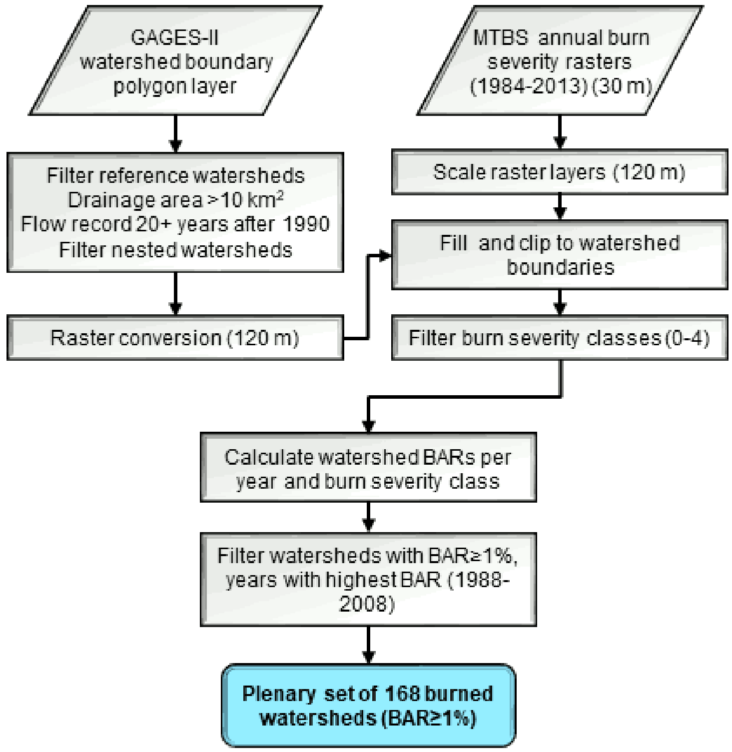


Figure 3. Development of the burned watershed database (adapted from Hallema and others 2018a). BAR, burn area to drainage area ratio; GAGES, Geospatial Attributes of Gages for Evaluating Streamflow; MTBS, Monitoring Trends in Burn Severity.

Evaluating Observed Wildland Fire Impacts on Annual River Flow

We conducted a comprehensive analysis of wildland fire effects on annual river flow using an assessment framework we designed for this purpose (Hallema and others 2017a, Hallema and others 2018a). This analysis was performed in a stepwise approach (fig. 4). First, we detected river flow (*Q*) change in the 5 year period after the fire relative to the 5 year period before the fire (step 1), and identified the corresponding change in water yield ratios (*Q/P*), which is the amount of river flow produced per unit of precipitation (step 2). Then, we characterized local interactions between BAR, watershed geometry, climate variability, topography and land cover (step 3). This enabled us to learn their relative impacts on the change in river flow (d*Q*), and to determine the minimum watershed BAR resulting in a change in annual river flow. Finally, we estimated the net impact of wildland fire on annual river flow (step 4).

Step 1: Detecting River Flow Change. We detected river flow change with the change point model (CPM). We used the cpm package in R (R Core Team 2017, Ross 2015) to loop through each time series of river flow data and compare the value distributions of river flow (Q) values before and after the evaluated time for a 10-year period, centered on the date on which the wildland fire occurs (Hawkins and others 2003, Hawkins and Zamba 2005). The null hypothesis was defined as no change in total monthly river flow (Q), evaluated with a statistical test [the non-parametric two-sample Lepage-type (L) statistic (Lepage 1971, Ross and others 2011)]. We rejected the null hypothesis if the statistical test indicated a shift in the baseline and range of these variations.

Step 2: Identifying Changes in Water Yield Ratio. Next, we detected changes in the monthly water yield ratio using double mass curves (DMCs) of cumulative river flow vs. cumulative precipitation. Fluctuations in the water yield ratio can point to changes in water use, water storage, or evapotranspiration in the basin (Searcy 1960). Here, we fitted linear regression models (the DMCs) to the 5-year pre-fire and 5-year post-fire periods, respectively. The null hypothesis was defined as no change in water yield ratio (dQ/dP), and like in step 1, evaluated with a statistical test [Chow's F-test (Chow 1960, Fisher 1970)]. We rejected the null hypothesis if the test statistic indicated a change in the water yield ratio.

Step 3: Characterizing Local Wildland Fire-Climate-Environment Interactions. We used gradient boosting techniques (Friedman 2001, 2002) to determine nonlinear relationships and interactions between river flow, wildland fire characteristics, climate variability, topography, land cover, and watershed geometry (Hallema and others 2018a, 2018c). Gradient boosting is a machine learning technique, common in data analytics, that generates regression trees of randomly selected subsamples in a stepwise process. At each iteration, we optimized the regression trees and calculate the relative influence of each variable as an indicator of how strongly they affected annual river flow. We introduced a random variable to the gradient boosting machine to be able to distinguish the variables with a significant influence on river flow, from the variables without significant influence. For this analysis we used the software gbm (Ridgeway 2013). This software has previously been applied in studies on river flow prediction and trend analysis (Erdal and others 2013, Rice and others 2015).

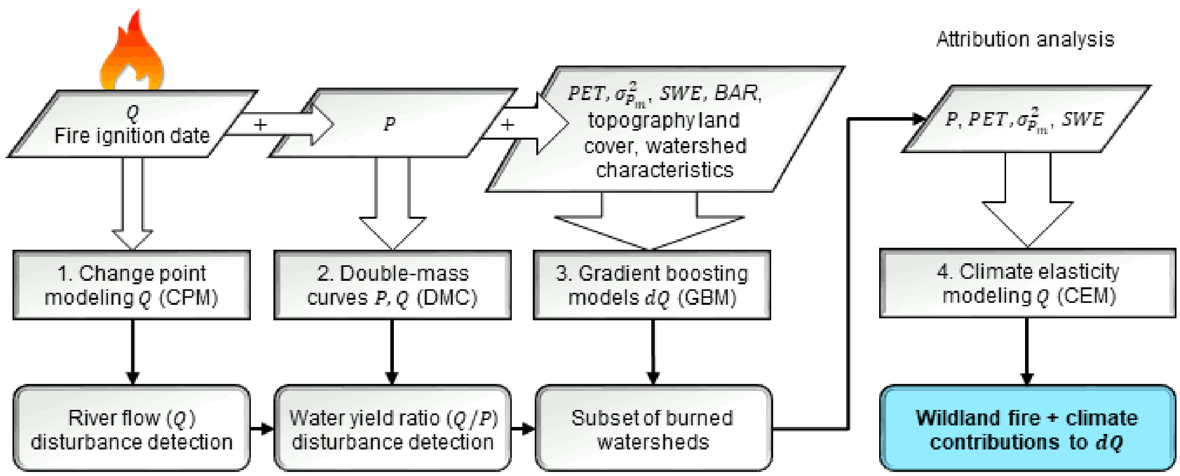


Figure 4. Wildland fire and climate contributions to change in river flow were determined using 4 analyses (adapted from Hallema and others 2018a). These four analyses (from left to right) combine data (top row) for river flow, wildland fire ignition date, climate, and burn characteristics. BAR, burn area to drainage area ratio; *Q*, river flow; *P*, precipitation; $\sigma^2_{P_m}$, monthly precipitation variance; SWE, snow water equivalent; PET, potential evapotranspiration; BAR, burned area to drainage area ratio.

Table 2. Climate elasticity models of river flow used in the attribution analysis (adapted from Hallema and others 2018a). α and β are model coefficients. CEM, climate elasticity model; *Q*, river flow; *P*, precipitation; PET, potential evapotranspiration; $\sigma^2_{P_m}$, monthly precipitation variance; SWE, snow water equivalent.

Climate Elasticity Model	Variables Included	Definition
CEM_0	River flow	$\frac{dQ}{Q_0} = 0$
CEM_1	River flow, precipitation	$\frac{dQ}{Q_0} = \alpha \frac{dP}{P_0}$
CEM_2	River flow, precipitation, potential evapotranspiration	$\frac{dQ}{Q_0} = \alpha \frac{dP}{P_0} + \beta \frac{dPET}{PET_0}$
CEM_3	River flow, precipitation, monthly precipitation variance	$\frac{dQ}{Q_0} = \alpha \frac{dP}{P_0} + \beta \frac{d\sigma^2_{P_m}}{\sigma^2_{P_{m,0}}}$
CEM_4	River flow, precipitation, snow water equivalent precipitation	$\frac{dQ}{Q_0} = \alpha \frac{d(P - SWE)}{(P_0 - SWE_0)} + \beta \frac{dSWE}{SWE_0}$

Step 4: Filtering Local Climate Baseline. In this step we filtered the local climate baseline from the river flow data to derive and estimate of the net impact of wildland fire on river flow (fig. 4). We established this baseline for each watershed individually by fitting climate elasticity models (CEMs) of river flow, defining the climate variability effect on changes in annual river flow (table 2) (Hallema and others 2018a). These CEMs of river flow are conceptual watershed models capturing complex spatial and time-dependent variations in evapotranspiration, subsurface storm flow, groundwater flow and river flow in terms of the local water balance (Hallema and others 2017a, Sankarasubramaniam and others 2001, Schaake 1990). CEM0 was a reference model and assumes no change in river flow. The other CEMs defined the change in river flow in terms of changes in precipitation dP (CEM1), dP and changes in potential evapotranspiration dPET (CEM2), dP and changes in monthly precipitation variance $d\sigma_{P_m}^2$ (CEM3), and dP and changes in snow water equivalent precipitation dSWE (CEM4). We fitted the models for each site and selected the CEM with the best performance, indicated by the lowest value of the Bayesian information criterion (BIC) (Schwarz 1978).

Bringing the Data Together. Finally, we calculated the net impact of wildland fire disturbance on river flow in watersheds with a potential wildland fire impact, as indicated by significance testing of the CPMs and DMCs, and the BAR, which must exceed the threshold level BARt. For watersheds with BAR ≥ BARt, we assumed that disturbance by wildland fire accounted for the change in river flow not explained by the climate elasticity model. The change in river flow caused by wildland fire was then calculated as the difference between the observed change in river flow, and the elasticity of river flow expected based on climate variability (Hallema and others 2017a, Hao and others 2015, Wei and others 2010). The CEM was very useful for this purpose because it measures the sensitivity of river flow to changes in precipitation, potential evapotranspiration, monthly precipitation variance and changes in snow water equivalent.

Predicting Potential Wildfire Effects on Surface Water Yield

We used the Water Supply Stress Index model (WaSSI; Sun and others 2008, Sun and others 2011) to obtain a full cover assessment of the potential impact of severe wildfire on surface water yield across the large climatic gradient of the Contiguous United States. To this end, we defined four scenarios of hypothetical burn impacts, and simulated corresponding changes to the water balance in all CONUS watersheds for the period between 2001 and 2010. By comparing the results of each scenario to a baseline scenario representing undisturbed conditions, we obtained an estimate of their hypothetical impact on water supplies.

First, we created the baseline scenario of the WaSSI integrated monthly water balance and flow routing model, by integrating the hydrologic cycle for up to 10 different land cover classes (crop, deciduous forest, evergreen forest, mixed forest, grassland, open shrubland, wetland, water, urban and barren land) in each of the 88,000 12-digit Hydrologic Unit Code (HUC-12) watersheds (fig. 5) comprising the CONUS. These watersheds correspond with a sixth-level hierarchical unit derived from the Watershed Boundary Dataset (WBD) and each drain an area of 95 km^2 on average. Individual watersheds vary in size between 0.2 km^2 and 9,200 km^2.

We parameterized the model using existing national-scale data for soil properties, land cover, monthly precipitation and monthly temperature (table 3) (Caldwell and others 2012). We scaled each of these datasets to the HUC-12 scale based on area-weighted averaging scheme using a Geographic Information System (GIS). Then we used WaSSI to calculate for each watershed the water balance and the fate of water received from precipitation as follows. First, WaSSI distinguished the respective contributions of rainfall and snowfall to the total precipitation using a conceptual snow model (McCabe and Markstrom 2007, McCabe and Wolock 1999). Then it calculated infiltration, surface runoff, soil moisture, and baseflow for individual land cover types within each watershed (Burnash 1995, Burnash and others 1973) using the Sacramento Soil Moisture Accounting Model (SAC-SMA) incorporated in WaSSI.

WaSSI simulated the monthly evapotranspiration (ET) for each land cover type based on high frequency eddy covariance measurements and remotely-sensed monthly leaf area index (LAI), Hamon potential ET (PET) calculated from the local latitude and monthly average temperature, and precipitation (Sun and others 2008). Because most watersheds contain a variety of different land cover classes, we computed the area-weighted average, resulting in ET estimates for each individual watershed. This estimate was bounded by the water supply rate from soil moisture to a depth of 2.5 m. We calculated this with SAC-SMA algorithm to correctly represent soil water supply-limited evapotranspiration, a phenomenon observed during periods of water stress when the atmospheric demand surpasses the supply rate of water by the soil. The water supply volume for each watershed equals:

$$Water\ yield = Precipitation - Evapotranspiration - Change\ in\ soil\ water\ storage$$

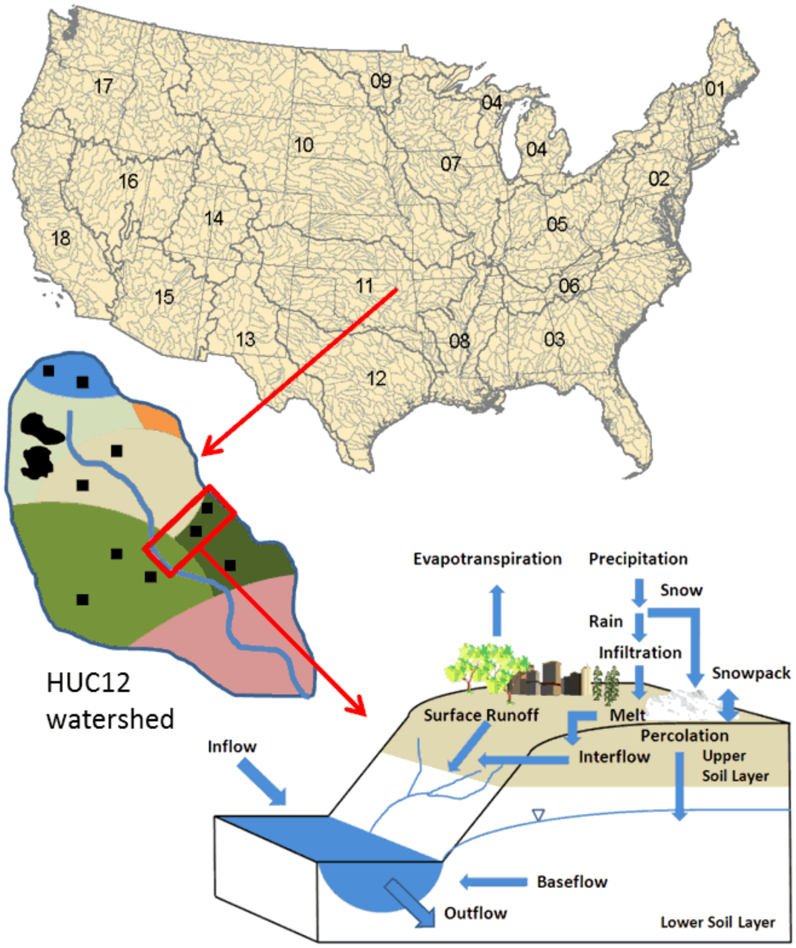


Figure 5. Schematic diagram illustrating the hydrological processes simulated by the Water Supply Stress Index model (WaSSI). WaSSI uses national scale databases to predict surface water yield (surface flow and baseflow) over the Contiguous United States at the HUC-12 watershed scale (adapted from Caldwell and others 2012).

Table 3. Data inputs for the Water Supply Stress Index (WaSSI) model (adapted from Caldwell and others 2014).

Data	**Source**	**Resolution**	**Time Period**
Soil properties	STATSGO-based Sacramento Soil Moisture Accounting Model Soil parameters and NOAA-NWS Hydrology Laboratory. Office of Hydrologic Development.	1 X 1 km grid	-
Land-cover distribution	National Land Cover Database for the Conterminous U.S. (http://mrlc.gov/nlcd06_data.php)	30 X 30 m grid	2006
Monthly mean Leaf Area Index (LAI) by Land Cover	Moderate Resolution Imaging Spectroradiometer (MODIS) (http://modis.gsfc.nasa.gov/)	1 X 1 km grid	2000-2006
Climate (monthly precipitation and temperature)	PRISM Climate Group (http://www.prism.oregonstate.edu/)	4 X 4 km grid	2001-2010
Watershed boundaries	Watershed Boundary Dataset (WBD) (http://nhd.usgs.gov/wbd.html)	HUC-12 (~95 km^2)	-

The WaSSI model has been tested under a wide range of hydroclimatic conditions (Caldwell and others 2012, Sun and others 2015a). WaSSI has been successfully applied in previous studies, including assessments of climate change and land cover/land use change on surface water supplies across the Contiguous United States (Caldwell and others 2014, Duan and others 2016) inclusive of Puerto Rico (Cohen and others 2017), and in Rwanda, Africa (McNulty and others 2016). WaSSI has also been used to distinguish wildland fire effects on surface water supplies from climate variability impacts (Hallema and others 2017a). More details on the WaSSI model, equations and applications are provided in Sun and others (2008) and Caldwell and others (2012).

Scenario 1: Soil hydraulic disturbance. Reduction of soil water storage by 50% across all watersheds. This scenario mimics a change in the water balance associated with post-fire soil surface sealing and fire-induced water repellency, the former being the more common cause of increased runoff after high severity wildfires (Larsen and others 2009, Hallema and others 2017b).

Fire-induced water repellency has been observed in the Colorado Rockies (Ebel and Moody 2012), in Southern California (Hubbert and others 2012) and elsewhere in the Southwest (Jian and others 2018). This phenomenon is ascribed to organic materials volatilized by the heat of a fire, and then precipitate locally as a hydrophobic coating that reduces infiltration and increases runoff (DeBano 1981, DeBano and others 2000). Others have cited hyper-dry conditions (Ebel and Moody 2013) and the degradation of soil structure by vaporized pore water (Jian and others 2018, Shillito and others 2018) as possible causes of reduced post-fire infiltration.

But runoff also increases in locations without post-fire soil water repellency (Doerr and others 2006, Meyer and Wells 1997), and can often be ascribed to a process known as soil surface sealing (Jordan 2016, Meyer and others 2001). Soil surface sealing can occur after a severe fire consumes the forest canopy. In the absence of leaf cover to intercept precipitation, the soil surface is exposed to the direct impact of precipitation. The direct impact of precipitation is sufficient to compact the soil surface, and reduce the infiltration capacity. Reduced infiltration causes the excess water to run off along the surface, and this mechanism is a common occurrence in a variety of landscapes (Hallema 2011), including fire-affected forests in the American West (Martin and Moody 2001).

Infiltration-excess runoff is not generated in equal amounts along a burned hillside. Rather, the amount of infiltration, runoff, and re-infiltration of runoff generated uphill, vary over short distances and change over the course of a single rain storm. We have not simulated variations in the runoff generating mechanism at such a small scale across the CONUS, but instead, we calculated the resulting potential effect on the local water balance by reducing the soil water storage capacity by 50%. In WaSSI, this translates into a 50% runoff ratio, which is within the 21%-67% range observed for a variety of post-fire runoff mechanisms in Colorado (Larsen and others 2009).

Scenario 2: Vegetation disturbance. Reduction of LAI for all land cover types by 50% across all watersheds. This scenario describes the change in evapotranspiration caused by fire-induced leaf loss. The postwildfire change in evapotranspiration depends on burn severity, and the associated degree of leaf loss, reduced surface shading and increased albedo (Dore and others 2012, Driscoll and others 2004, Montes-Helu and others 2009). A 50% reduction of LAI has been observed as a result of high severity burn impacts in Arizona coniferous forests (Dore and others 2012), and we assume in this scenario that this degree of LAI change is typical of all vegetated areas affected by fire.

Scenario 3: Soil hydraulic disturbance and vegetation disturbance. This scenario combines a 50% reduction in soil water storage capacity with a 50% reduction in LAI across all watersheds, reflecting the potential fire impact on runoff generation and the evapotranspiration of vegetative land cover types. This scenario, like scenario 1 and scenario 2, reflects changes in all vegetative land cover types including forest, shrubland and grassland.

Scenario 4: Forests burned over 20% of their area (observed threshold response). For watersheds with a forest cover greater than 20%, assume that 20% of the watershed area was burned, all of which is forest, with a reduction in LAI of 80% in these areas. Watersheds with a forest cover smaller than 20% are not considered. This scenario applies the minimum burned area threshold of 20% we observed for impacts on annual river flow across 168 CONUS watersheds (section "Factors Contributing to Changes in River Flow"). The 50% LAI reduction reflects a broad range of observed wildfire impacts on vegetation (De Santis and Chuvieco 2008, Meigs and others 2008).

RESULTS

Burn Characteristics of Gaged Watersheds

We identified 168 watersheds in the CONUS (fig. 6) burned over more than 1% of their land area (BAR ≥ 1%) by a wildland fire between 1985 and 2008 (fig. 7). These burned watersheds constituted the plenary set used in this study and included various types of wildland fires, such as wildfires and prescribed fires. 31% of the burned watersheds were located east of the Mississippi River (52 burned watersheds) and the remaining 69% west of the Mississippi River (112 burned watersheds).

The median size of burned CONUS watersheds was 404 km^2, with a median BAR of 5.8% (table 4). The largest burned watersheds were located in the Arkansas-White-Red River (median 1,820 km^2) and Pacific Northwest (529 km^2) water resource regions and the smallest burned watersheds were located in the Great Basin (70 km^2) and California regions (243 km^2). The proportion of the watershed area burned at moderate to high severity was generally small (0.7%) compared to the combined underburned area and area burned at low severity (4.7%) (fig. 8).

High median burned area to drainage area ratios were observed in mid to high elevation watersheds (>800 m) in California (20.6%), Lower Colorado (15.4%), and Pacific Northwest (13.5%) regions, which also had the highest BARs for mid to high burn severity classes (4.6%, 3.8% and 3.7%, respectively). Watersheds with high BARs were often small headwater catchments, especially in the California region and the Lower Colorado region. Low BARs were observed in relatively large low-elevation (<800 m) watersheds like those in the Texas-Gulf region (2.3%), and in the South Atlantic-Gulf region (3.1%) where low severity prescribed fires are more common (2.5%).

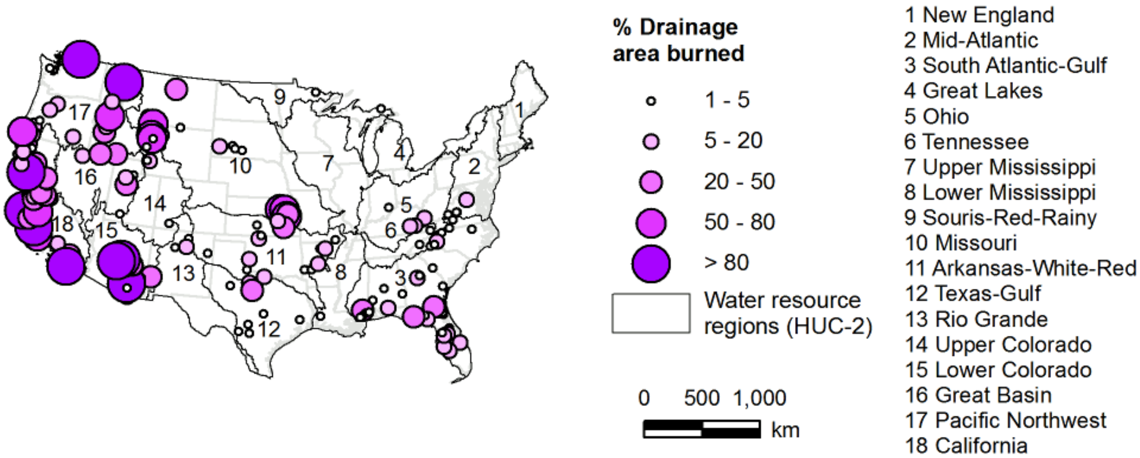


Figure 6. CONUS watersheds burned in individual wildland fires between 1985 and 2008 (*n*=168 burned watersheds with BAR ≥ 1%) (adapted from Hallema and others 2018a).

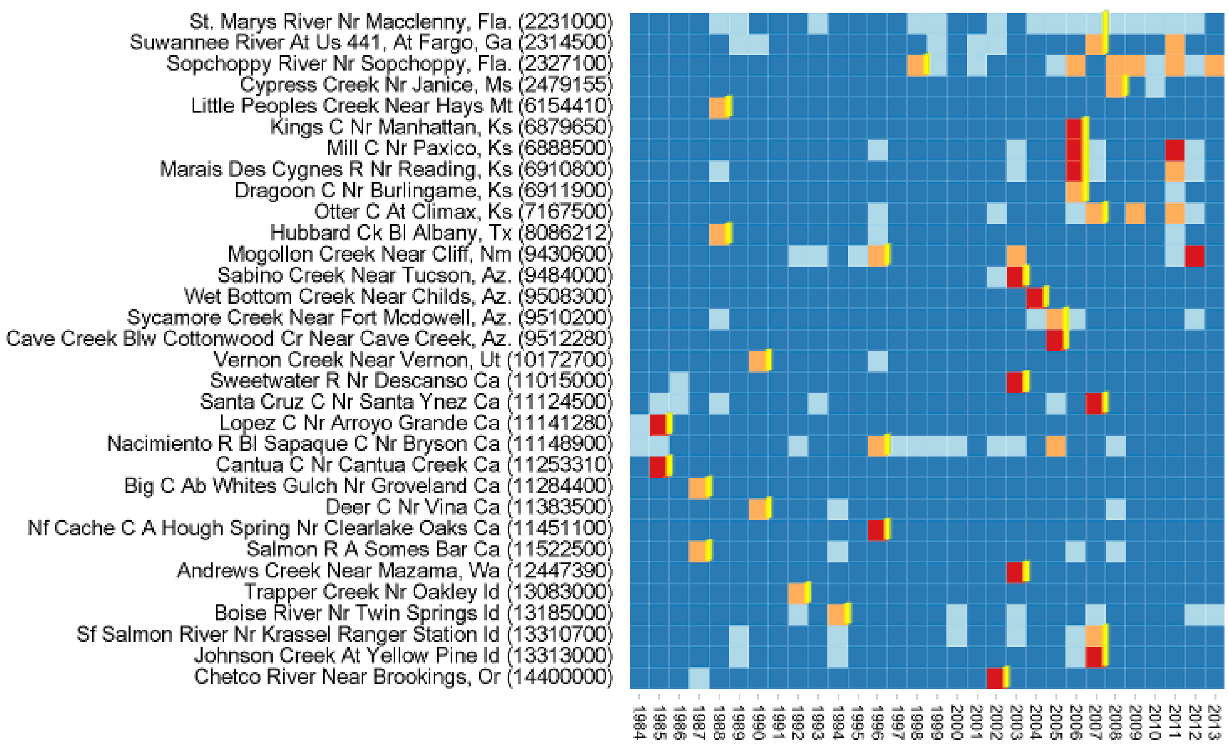


Figure 7. Heat map of the annual burned area to drainage area ratios (BAR) for 32 CONUS watersheds with BAR ≥ 19%, 1984-2013 by USGS flow gauge number (vertical axis). Key: steel blue - BAR = 0% (no fire), light blue 1%-20%, orange 20%-50%, red >50%. Studied fire years marked with yellow.

Table 4. CONUS observed changes in post-wildland fire annual river flow (Hallema and others 2018a). Values represent changes in 5-year mean river flow (*dQ*), grouped by water resource region for watersheds burned between 1985 and 2008 (BAR ≥ 1%) (median values per region). The 5-year mean precipitation (*dP*) and river flow (*dQ*) were divided by the drainage area to allow comparison, with resulting units in millimeters.

Water Resource Region	HUC-2 Region Code	Number of Watersheds	Drainage Area (km^2)	BAR (%)	BAR Underburned-Low Severity (%)	BAR Moderate-High Severity (%)	*dQ* (mm)	*dQ* (%)	*dP* (mm)	*dP* (%)
Mid Atlantic	2	4	547	3.1	2.6	0.5	-97.4	-16.5	-59.5	-4.3
South Atlantic-Gulf	3	37	413	3.1	2.5	0.1	-44.0	-12.9	-22.2	-1.3
Great Lakes	4	1	1910	1.8	0.3	1.5	-20.5	-5.1	-19.1	-2
Ohio	5	4	589	8.9	8.7	0.1	54.0	12.8	92.3	7.1
Tennessee	6	2	456	1.8	1.7	0.1	-69.0	-11.6	-76.6	-4.9
Lower Mississippi	8	3	342	4.8	4.3	0.2	160.1	27.4	311.2	23.3
Souris-Red-Rainy	9	1	2358	1.1	0.5	0.6	47.0	21.2	43.9	6.2
Missouri	10	15	471	6.0	2.9	0.2	-3.2	-5.3	20.3	2.1
Arkansas-White-Red	11	13	1820	4.2	4.2	0	1.4	16.0	53.7	4.6
Texas-Gulf	12	8	435	2.3	1.3	0.3	-10.7	-25.4	-26.6	-0.8
Rio Grande	13	3	163	4.5	1.4	3.0	-15.6	-29.8	-100.8	-13.1
Upper Colorado	14	3	333	2.5	1.3	2.2	77.5	19.8	41.9	6.9
Lower Colorado	15	15	425	15.4	9.3	3.8	9.9	25.6	-30.6	-6.0
Great Basin	16	5	70	5.8	5.3	0.9	-45.4	-37.1	0.7	0.1
Pacific Northwest	17	25	529	13.5	10.4	3.7	21.3	5.6	-28.5	-3.3
California	18	29	243	20.6	9.9	4.6	-38.4	-18.4	-35.4	-4.6
Contiguous United States		168	404	5.8	4.7	0.7	-5.9	-5.7	-23.1	-2.3

Abbreviations: BAR, burned area to drainage area ratio; HUC, Hydrologic Unit Code

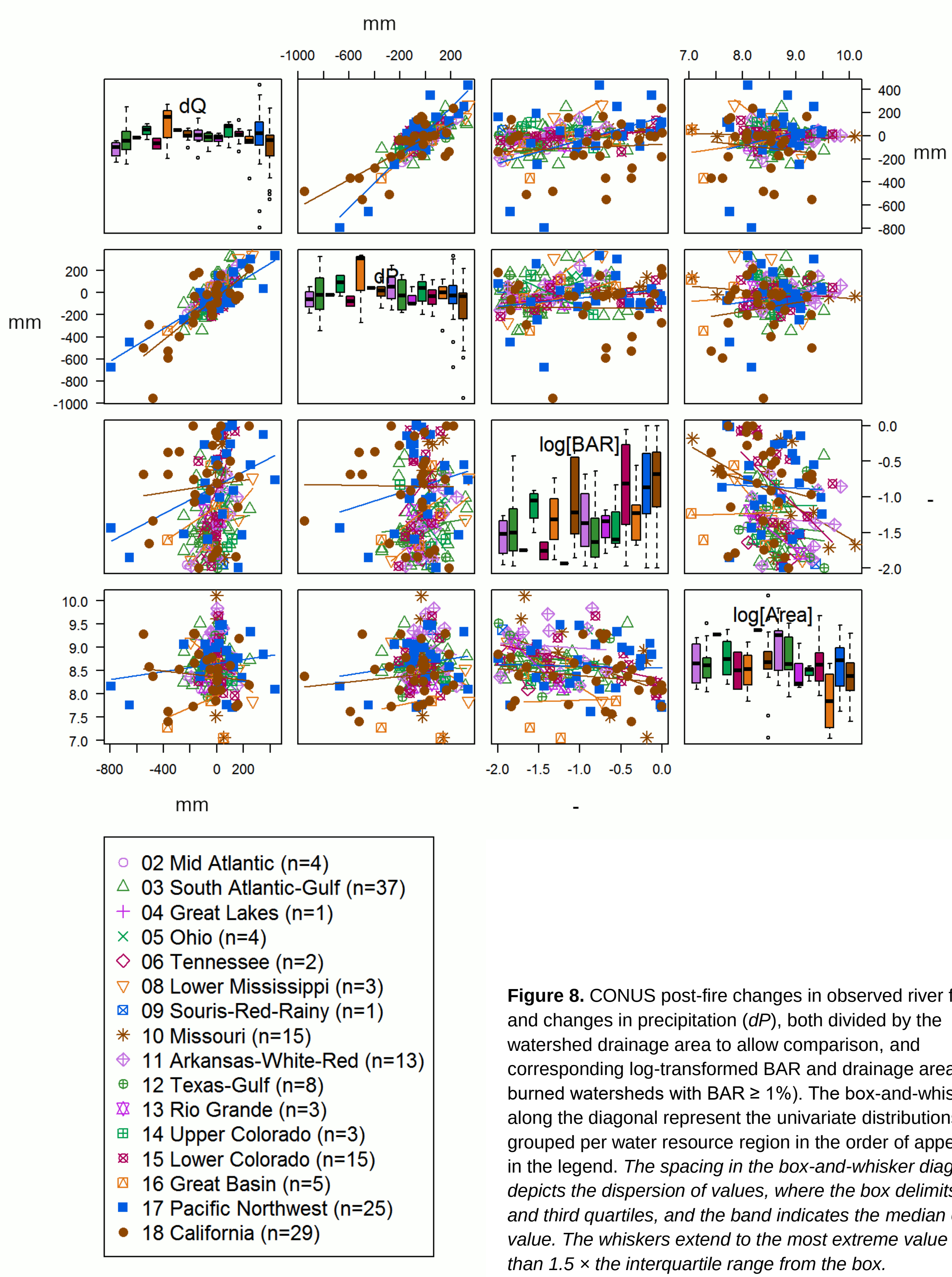


Figure 8. CONUS post-fire changes in observed river flow (*dQ*) and changes in precipitation (*dP*), both divided by the watershed drainage area to allow comparison, and corresponding log-transformed BAR and drainage area (*n*=168 burned watersheds with BAR ≥ 1%). The box-and-whisker plots along the diagonal represent the univariate distributions, grouped per water resource region in the order of appearance in the legend. *The spacing in the box-and-whisker diagram depicts the dispersion of values, where the box delimits the first and third quartiles, and the band indicates the median or middle value. The whiskers extend to the most extreme value no more than 1.5 × the interquartile range from the box.*

Observed Post-Fire Annual River Flow in Gaged Watersheds

Flow records from 168 gaging stations in the CONUS showed that the 5-year mean annual river flow decreased after wildland fire in nine water resource regions (table 4) (Hallema and others 2018a): the Mid Atlantic, Tennessee, Great Basin, South Atlantic-Gulf, California, Great Lakes, Rio Grande, Texas-Gulf, and Missouri regions. Conversely, flow increased in six other regions: the Lower Mississippi, Upper and Lower Colorado, Ohio, Pacific Northwest, and Arkansas-White-Red River regions. To allow comparison, we divided river flow (units $L^3.T^{-1}$, *e.g.* cubic feet per second) by the drainage area of the watershed (L^2) with resulting units in millimeters (mm). Generally, 5-year post-wildland fire river flow decreased in burned watersheds, with a CONUS median change of -5.9 mm (-5.7%). The timing of these reductions in Q corresponded with declining trends in precipitation (median change of -23.1 mm or -2.3%).

The relative decrease in river flow was greatest in burned watersheds of the Great Basin (median of -45.4 mm or -37.1%), Rio Grande (-15.6 mm or -29.8%), Texas-Gulf (-10.7 mm or -25.4%) and California (-38.4 mm or -18.4%) regions. The greatest decline in precipitation was recorded for the Rio Grande (-100 mm or -13.1%), Lower Colorado (-30.6 mm or -6.0%), California (-35.4 mm or -4.6%), and Mid Atlantic (-59.5 mm or -4.3%) regions. Flow increase was greatest in the Lower Mississippi (median of +160.1 mm or +27.4%), and Upper Colorado (+77.5 mm or +19.8%) regions.

Factors Contributing to Changes in Annual River Flow

The changes in annual river flow were linked with a myriad of factors and their interactions, such as climate, wildland fire, topography, land cover, and geometrical characteristics of the watershed (*e.g.*, drainage area). Interannual variations in climate are the main driver causing a change in annual river flow (fig. 9a) for all watersheds with BAR<1% regardless of fire type (wildfire, prescribed burn, or other wildland fire). The change in annual precipitation had an influence of 47.4% on the change in river flow, the change in precipitation variability (8.3%), pre-fire precipitation variability (4.5%), post-fire precipitation variability (4.1%), and change in snowfall (3.6%), assuming that the total influence of all factors contributing to the change in river flow in the CONUS equaled 100%.

The watersheds west of the Mississippi River have a higher elevation and steeper terrain, which increased the impact of extreme climate on river flow. In the Eastern watersheds, land cover had a secondary influence on river flow after climate. The size of area burned was a secondary influence on river flow when a CONUS watershed was burned over approximately one fifth (19%) of its area or more (fig. 9b) (Hallema and others 2018a). Areas within the fire perimeter with high severity burn impacts had a greater influence (2.8%) than areas with moderate (2.2%) impacts, and low burn severity had no detectable impact on river flow in the evaluated watersheds.

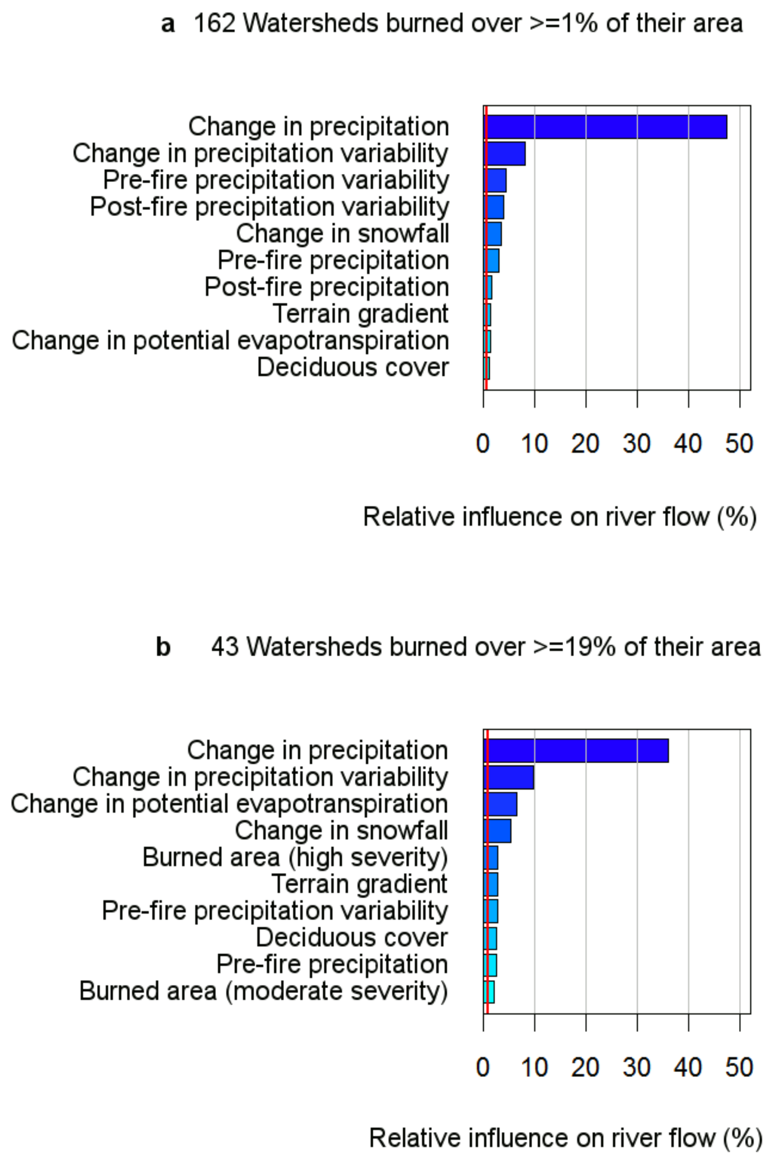


Figure 9. Climate-related factors had the greatest influence on the change in annual river flow in the CONUS in the 5 years after a wildland fire (a) (adapted from Hallema and others 2018a). But, the area burned represented a secondary influence on river flow for watersheds burned over one fifth (19%) of their area or more (b). Areas within the fire perimeter with high severity burn impacts had a greater influence than areas with moderate or low burn severity impacts. *The red line represents the influence of a random variable, shown for reference.*

Wildland Fire Impact on Annual River Flow Observed across the Contiguous United States

Wildland fire affected the annual river flow in watersheds with more than one fifth (19%) of their area burned. The majority of these burned watersheds were located in the water resource regions west of the Mississippi River (28 burned watersheds in regions 10-18), and a smaller number are located east of the Mississippi River (4 burned watersheds in region 3). There was a marked difference between east and west of the Mississippi River—flow recorded at the outlet of these burned watersheds increases in the West, and decreases in the East (fig. 10).

By separating the respective contributions of interannual climate variations and wildland fire to the change in river flow, we found that river flow in the East was even lower than predicted based on the variations in climate. Conversely, wildfires in the West partially offset the flow-reducing effect of climate trends. At the CONUS scale, the median 5-year post-fire annual river flow increase from watersheds burned over at least one-fifth of their area was +34 mm (+14.0%). To allow comparison of water yield in different areas, we divided river flow (units $L^3.T^{-1}$, *e.g.* cubic feet per second) by the drainage area of the watershed (L^2) with resulting units in millimeters (mm). Interannual climate variations alone led to a median flow decrease of -8.3 mm (-3.9%), while fires enhanced river flow, with a median increase of +19.3 mm (+14.6%).

Wildland fire impacts on annual river flow varied greatly between regions. Across the West, wildfires increased median flow by +22.3 mm (+18.9%). Results for the East were influenced by severe tropical weather events, and therefore the outcomes of the attribution analysis represent the compound effect of multiple disturbances. The greatest impact in absolute terms occurred in the Pacific Northwest water resource region, but the greatest impact as a percentage change was observed in the Lower Colorado region (fig. 11).

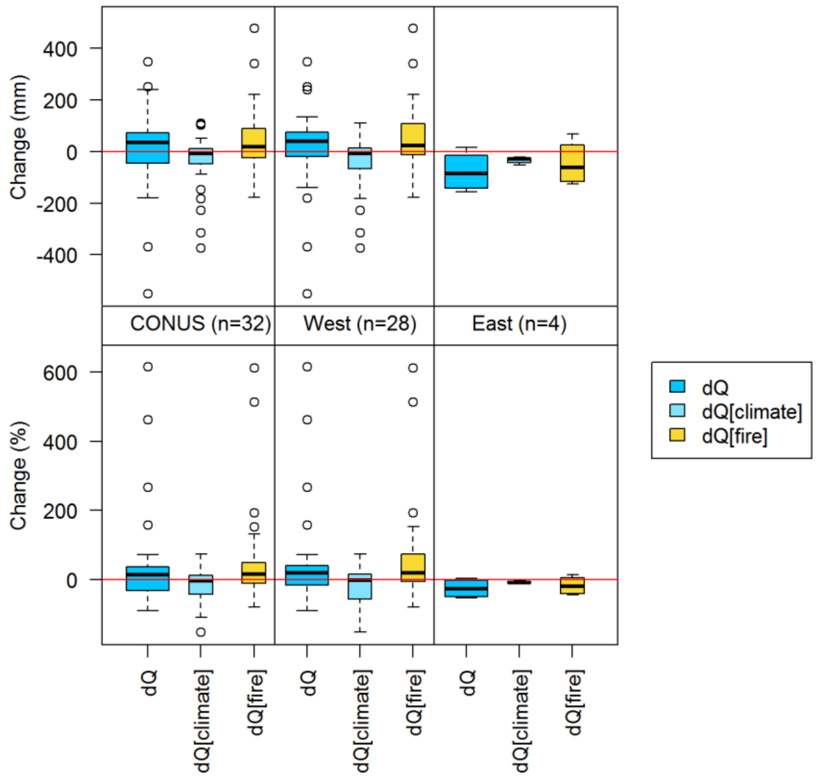


Figure 10. CONUS-East-West comparison of the change in 5-year mean annual river flow observed by USGS gages (*dQ*) in watersheds with over >19% of their area burned, and change attributed to climate (*dQ*[climate]) and wildland fire (*dQ*[fire]), respectively. *Changes are shown in mm (above) and percentage (below). The Eastern and Western CONUS include water resource regions 3 and 10-18, respectively. The boxes contain 50% of the values, and the band indicates the median or middle value. Whiskers extend to the most extreme values no more than 1.5 × the interquartile range from the box.*

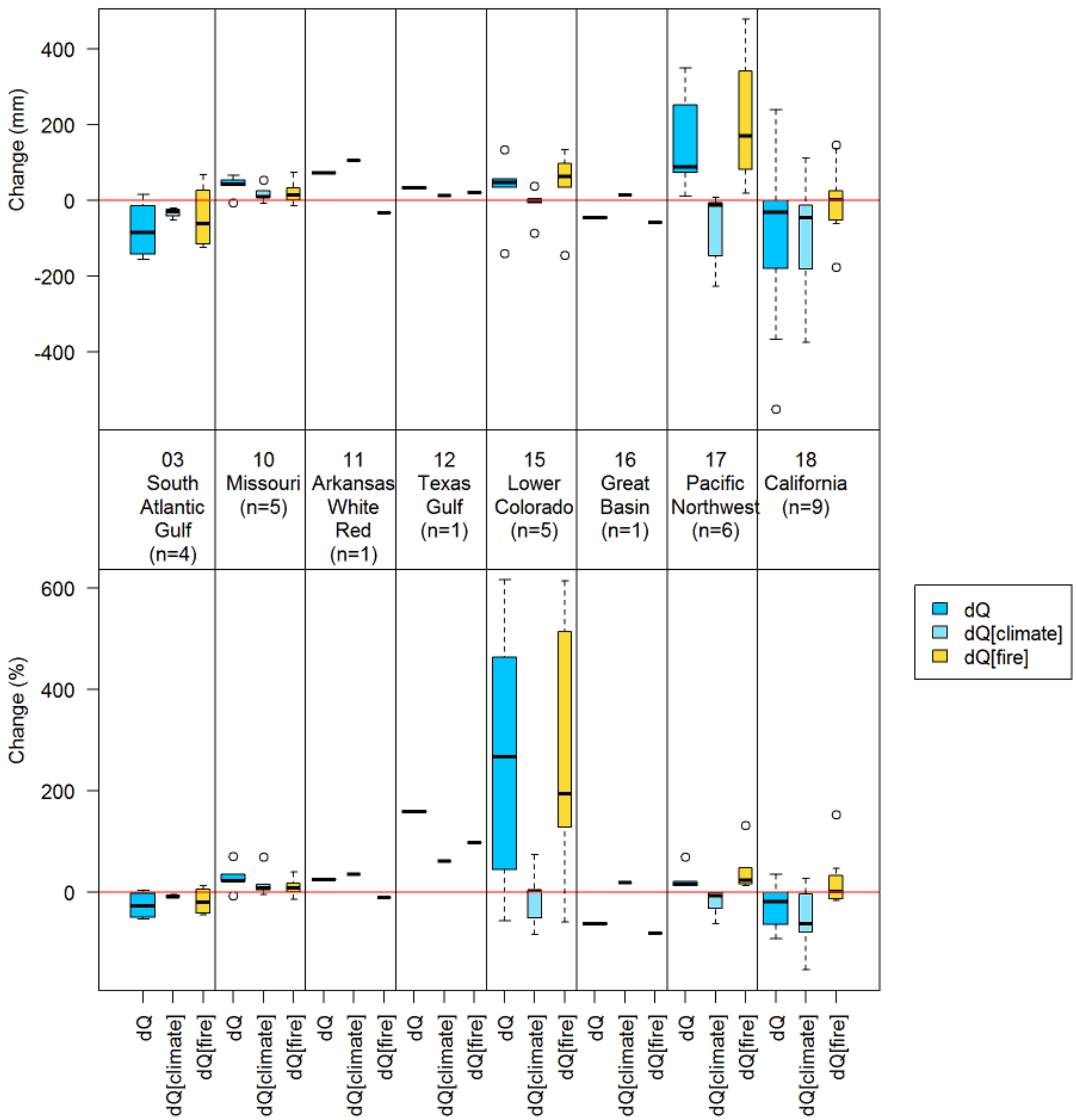


Figure 11. CONUS regional level comparison of the change in 5-year mean annual river flow observed by USGS gages (dQ), and attributed to climate (dQ[climate]) and wildland fire (dQ[fire]), respectively (32 burned watersheds burned over more than one fifth of their area). *Changes are shown in mm (above) and percentage (below). The boxes contain 50% of the values, and the band indicates the median or middle value. Whiskers extend to the most extreme values no more than 1.5 × the interquartile range from the box.*

South Atlantic-Gulf and Texas-Gulf Regions (Water Resource Regions 3 and 12)

Three of the four South Atlantic-Gulf burned watersheds are located on the Southeast coastal plain in Georgia and Florida, and the fourth burned watershed is located on the Mississippi Southeast plains (fig. 12). The climate of these watersheds is humid subtropical (Cfa) (Peel and others 2007; for key refer to Appendix A). The St. Marys River watershed (1,748 km^2) and the headwaters of the Suwannee River (3,322 km^2) form two adjacent watersheds at the border between Georgia and Florida. Both watersheds are partly located within the Okefenokee Swamp, and partly agriculturally developed. The St. Marys River watershed also comprises the eastern half of Osceola National Forest. A third watershed, the Sopchoppy River watershed in Apalachicola National Forest in West Florida, is much smaller in size (271 km^2) and covered by forest wetlands.

Appendix B shows for each of the 32 burned watershed the elevation, land cover and burn severity maps, and a table with corresponding information about topography, land cover, wildland fire, climate, and hydrology, and most importantly, the wildland fire impact on river flow. Wildfires burned between 19.3% and 37.7% of these watersheds in 2007 (St. Marys River watershed and Suwannee River watersheds) and in 1998 (Sopchoppy River watershed) and had mostly low burn severity impacts. Annual precipitation declined after the wildfires by -11.8% to -14.1% (fig. 11 and fig. 13). The decline in precipitation (-209 mm or -12.9%) explained most of the -43 mm (-6.8%) river flow reduction in the Sopchoppy River watershed, but it is likely that in the other two watersheds, a combination of human factors and the 2006 regional drought (Torak and others 2010) was responsible for the -156 mm (-46.9%) and -127 mm (-53.3%) respective abatements in river flow.

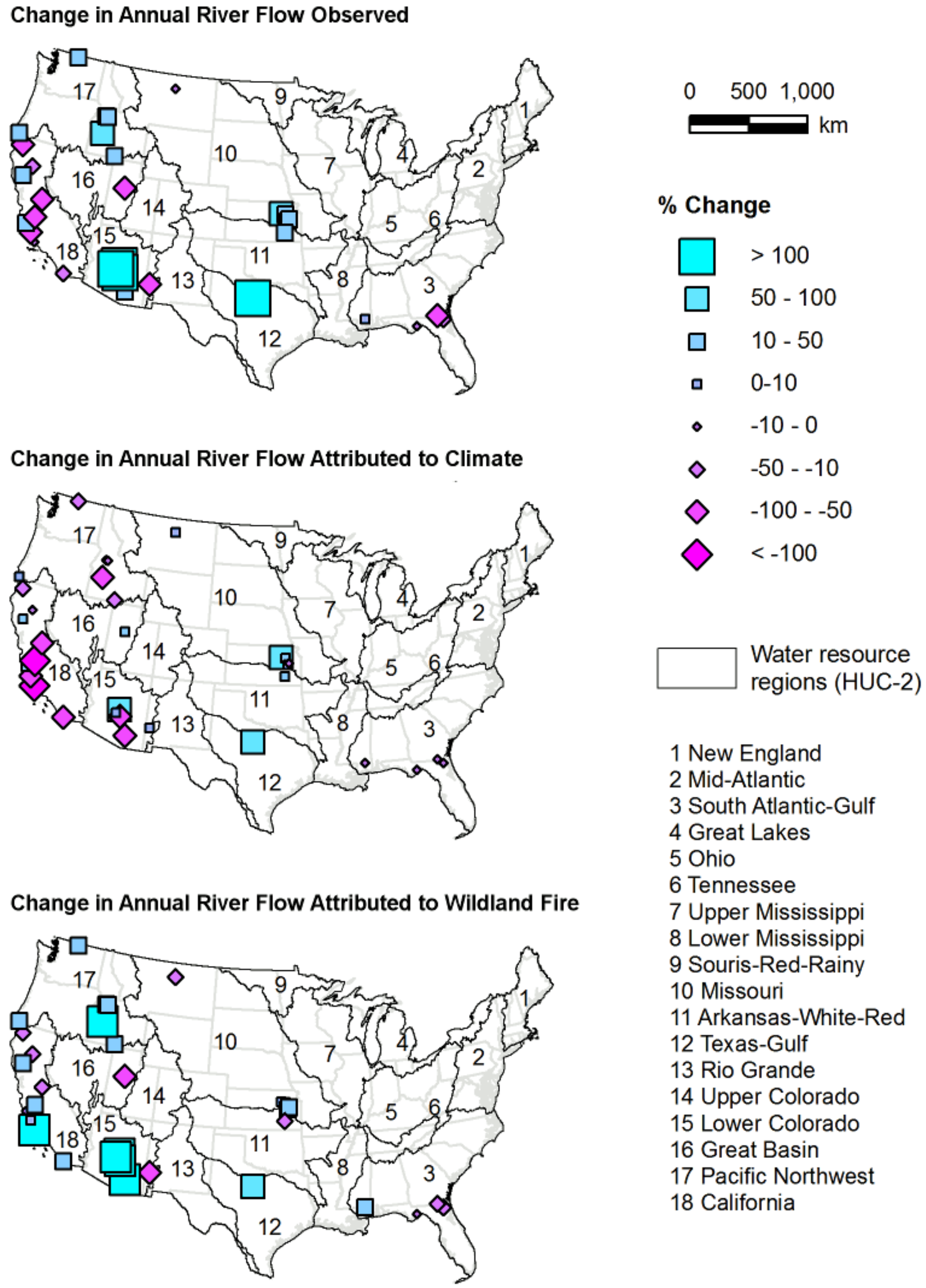


Figure 12. CONUS map showing the change in annual river flow observed by USGS gages, attributed to climate, and attributed to wildland fire, respectively (32 watersheds with more than one fifth of their area burned) (adapted from Hallema and others 2018a).

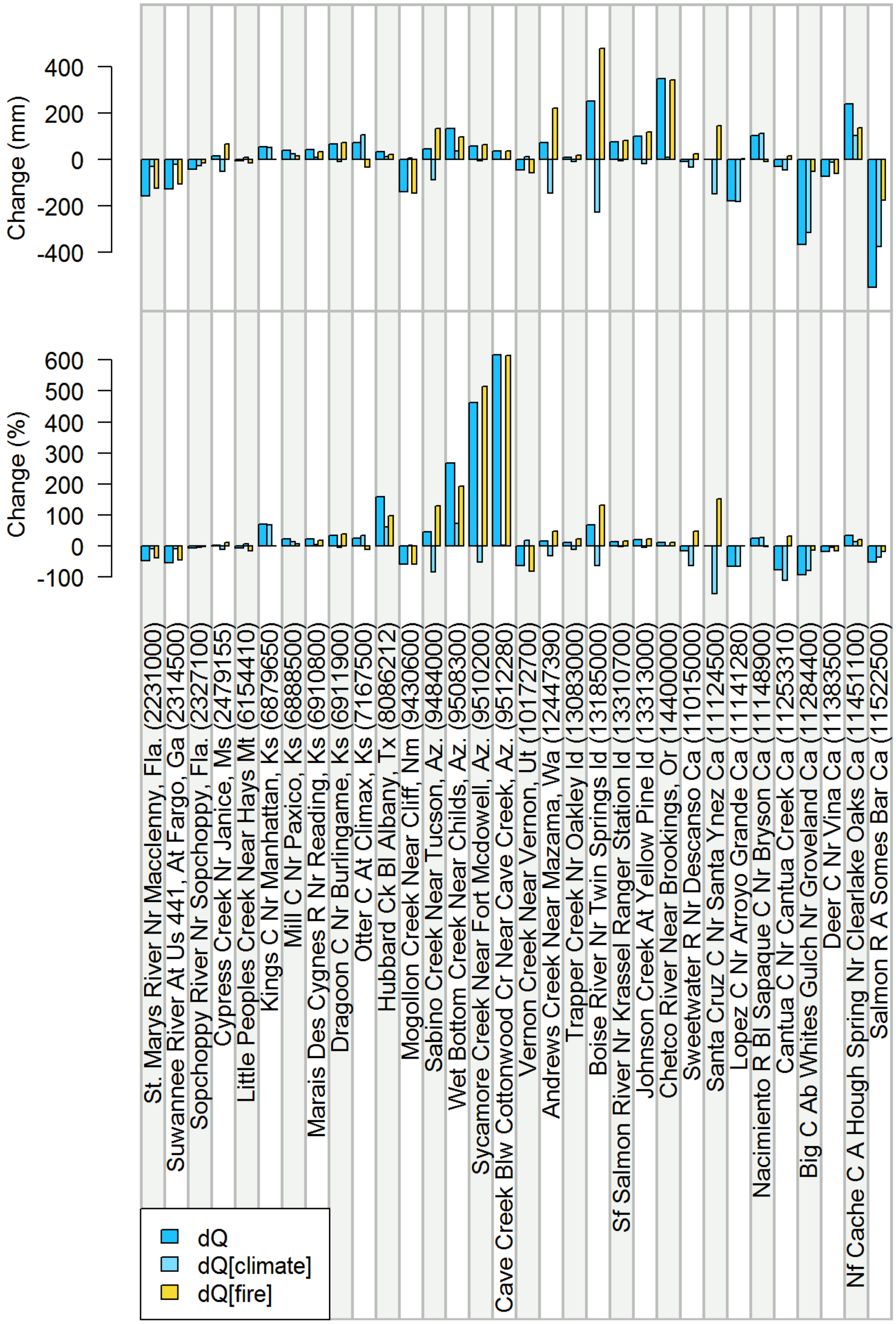


Figure 13. CONUS watershed level comparison of the change in 5-year mean annual river flow observed (d*Q*), and attributed to climate (d*Q*[climate]) and wildland fire (d*Q*[fire]), respectively (32 watersheds with more than one fifth of their area burned). *Changes are shown in mm (above) and percentage (below).*

The fourth watershed in the South Atlantic-Gulf region is the Cypress Creek watershed (137.3 km^2) within De Soto National Forest on the Mississippi Southeast plains. A prescribed fire burned 24.1% of the watershed, and this was the only prescribed fire in our database that burned more than one-fifth of a watershed. Other than fire, the watershed experienced a notable increase in precipitation (176 mm or +11.3%) accompanied by an increase in river flow (10 mm or +2.9%).

Nonetheless, the climate elasticity model (CEM_2) for Cypress Creek predicted a decline in river flow. The change point model indicated that the increased river flow erroneously ascribed to the prescribed fire, was in reality associated with Hurricane Katrina. This tropical cyclone traversed the watershed as a category 2 hurricane and killed millions of trees across the state of Mississippi (Oswalt and others 2008). A climate elasticity model based on actual evapotranspiration instead of PET may in this case yield a more accurate assessment of wildland fire-effects on river flow.

The Hubbard Creek watershed in central Texas (1,584 km^2) at an elevation between 369 and 669 m also has a humid subtropical climate (Cfa) except with a lower (700 mm) and more variable precipitation than the South Atlantic-Gulf watersheds (more than 1,400 mm). The 1988 Big Country Wildfire burned 23.2% of the watershed, mostly shrub vegetation. This wildfire contributed +20.4 mm (+97.6%) to the observed +33 mm (+158.7%) increase in river flow. An impact of this magnitude is partly explained by a variable terrain and low vegetative cover (49% shrubland and 35% grassland or herbaceous) compared to the South Atlantic-Gulf watersheds.

Missouri and Arkansas-White-Red Regions (Water Resource Regions 10 and 11)

Five of the six burned watersheds in the Missouri and Arkansas-White-Red regions are clustered together on the East Kansas Plains (fig. 12). These watersheds drain between 33.4 km^2 and 842 km^2 and lay at an elevation between 300 m and 500 m. The climate is humid continental with warm summers (Dfa). Wildland fires in 2006 and 2007 had a low burn severity and affected between 21.0% and 65.6% of the watershed drainage area. The largest fire by area was an unnamed fire in the Mill Creek watershed, which covered 509.1 km^2, or 60.5% of the watershed.

Annual river flow increased in the Mill Creek watershed with +39 mm (+22.7%) (fig. 13), of which +25.4 mm (+14.6%) can be explained by reduced drought and +13.9 mm (+8.0%) by fire. Similar conditions and river flow responses occurred in the Marais des Cygnes River watershed. Annual flow also increased in the Otter Creek watershed (+72 mm or +24.4%), but our climate elasticity models yielded mixed results for all five watersheds due to low flows or no flow in the summer. In the King's Creek watershed in Kansas, the small drainage area (11.5 km^2) did not produce any outflow during most of the year. We encountered a similar challenge for the Little Peoples Creek watershed in the upper quadrant of the Missouri basin, in Eastern Montana, where river flow was only 21 mm. The fire in the Dragoon Creek in Kansas was underburned, and had no impact on river flow.

Lower Colorado and Great Basin Regions (Water Resource Regions 15 and 16)

For the Lower Colorado and Great Basin regions, we assessed six mid to high-elevation burned watersheds (fig. 12), with highest points reaching 1,628 m (Cave Creek watershed in Arizona) to 3,261 m (Mogollon Creek watershed in New Mexico). All are located in National Forests: the Mogollon Creek watershed (191 km^2) in Gila National Forest, in New Mexico, the Wet Bottom Creek (93.0 km^2), Sycamore Creek (425 km^2), and Cave Creek (189 km^2) in Tonto National Forest in Arizona, the Sabino Creek watershed (104 km^2) in Coronado National Forest, also in Arizona, and the Vernon Creek watershed (69.9 km^2) in the Uinta National Forest in Utah.

The climate varies from cool dry-summer (Csb) in the New Mexico watershed to hot semi-arid (BSh) in the four Arizona watersheds, and is characterized as cold semi-arid (BSk) in the Utah watersheds. Precipitation ranged between 355 mm and 658 mm. Wildfires increased annual river flow by up to +133.6 mm (fig. 11), however, the percentage increase caused by wildfires were the highest observed in the CONUS: +613% (+35.0 mm) in Cave Creek, and +514.5% (+63.3 mm) in Sycamore Creek (fig. 13).

The high percentage change in runoff is explained by the small size and low annual river flow in these watersheds: 6-69 mm. Small watersheds are more sensitive to the seasonal distribution of precipitation, in particular given that in the Southwest, winters with a shallow snowpack are often followed by wet monsoons in the summer and vice versa (Higgings and Shi 2000, Notaro and Zarrin 2011). Both watersheds were also burned over a relatively large area, 75.5% and 39.5%, respectively, with moderate to high burn severity impacts affecting 26.7% and 18% of the watershed area, respectively.

Pacific Northwest Region (Water Resource Region 17)

The Pacific Northwest burned watersheds cover a wide range of climate types. The Chetco River burned watershed (703 km^2) in Oregon has a cool dry-summer climate (Csb), the Trapper Creek watershed (133 km^2) in Idaho has a cold semi-arid climate (BSk), and four other watersheds in Idaho and Washington (58 km^2 to 2,154 km^2) have a snow-dominated climate (Dsa or Dsb). These watersheds are located within the Siskiyou National Forest (Chetco River), Sawtooth National Forest (Trapper Creek), Boise National Forest (Boise River and Johnson Creek), Payette National Forest (South Fork Salmon River), and Okanogan National Forest (Andrews Creek) (fig. 12). Coniferous forest cover ranges between 45% and 79%, except in the Trapper Creek watershed, which is 89% covered by shrubs.

The Pacific Northwest is characterized by high runoff values associated with rainfall and snowmelt, therefore wildfires increased annual river flow substantially in absolutely terms in these cold climate watersheds (fig. 11), even though relative changes were lower than in the Lower Colorado region. In the Boise River near Twin Springs, flow increased by +478 mm (+131.9%) in the years following the Idaho City Complex (Rabbit Creek) wildfire that burned 28.3% of its watershed (fig. 13). A unique phenomenon in the flow records of two of these watersheds (Boise River and Andrews Creek), is an increase in flow, while interannual variability in climate suggested that flow would decrease. Wildfire partially overcame the reduction expected with drier post-fire weather patterns.

California Region (Water Resource Region 18)

The four burned watersheds located in Northern California (fig. 12) have a hot-summer Mediterranean climate (Csa), and the four burned watersheds in the Southern Coast Ranges have a warm-summer Mediterranean climate (Csb). A ninth watershed (Cantua Creek draining into the Central Valley) has a hot semi-arid climate (BWk). All except the Cantua Creek watershed are partially located within a National Forest: the Sweetwater River watershed is in the Cleveland National Forest, the Santa Cruz Creek, Lopez Creek, and Nacimiento River watersheds are located in Los Padres National Forest, the Big Creek watershed in Stanislaus National Forest, the Deer Creek watershed in Lassen National Forest, the North Fork Cache Creek watershed in Mendocino National Forest, and the Salmon River in Klamath National Forest. With a median drainage area of 155 km^2, these headwater catchments are smaller than the burned watersheds we evaluated for other regions.

The relatively small watershed area has both positive and negative consequences for the accuracy of the wildland fire effect assessment (fig. 11). The simulated climate elasticity of river flow is more prone to error if the area of interest is smaller. Conversely, we are more certain that the wildfires burning anywhere between 20% and 99% of these watersheds represent the major local disturbance during the evaluated period. Precipitation declined substantially in most watersheds (median -86.8 mm or -12.3%) as a result of drought. However, the observed river flow did not decline proportionally, indicating a positive fire influence on river flow change. The flow-enhancing effect of wildfire was masked by declining precipitation in three chaparral dominated watersheds in Southern California (Sweetwater River, Santa Cruz, and Cantua Creek watersheds) (fig. 13), which produced a net negative change in river flow.

Simulated Potential Wildfire Impact on Surface Water Yield across the Contiguous United States

WaSSI hydrological simulations of the four hypothetical burn scenarios across the 88,000 HUC-12 level CONUS watersheds for the period 2001 to 2010 revealed a wide range in surface water yield responses across the gradient of climate, vegetation, and topography of the CONUS. To allow comparison, we divided river flow (units $L^3.T^{-1}$, *e.g.* cubic feet per second) by the drainage area of the watershed (L^2) with resulting units in millimeters (mm). Annual water yield increased by +14 mm [soil hydraulic disturbance scenario (1) with 50% reduction in soil water storage], +33 mm [vegetation disturbance scenario (2) with 50% reduction in LAI], +45 mm [soil disturbance and vegetation disturbance scenario (3) with a 50% reduction in soil water storage and a 50% reduction in LAI], and +18 mm [scenario 4 where forests were burned over 20% of their area] on average across all CONUS HUC-12s compared to the baseline undisturbed condition (fig. 14). The corresponding average relative increases in surface water yield were +5%, +11%, +16%, and +6%, respectively, under the four burn impact scenarios (fig. 15).

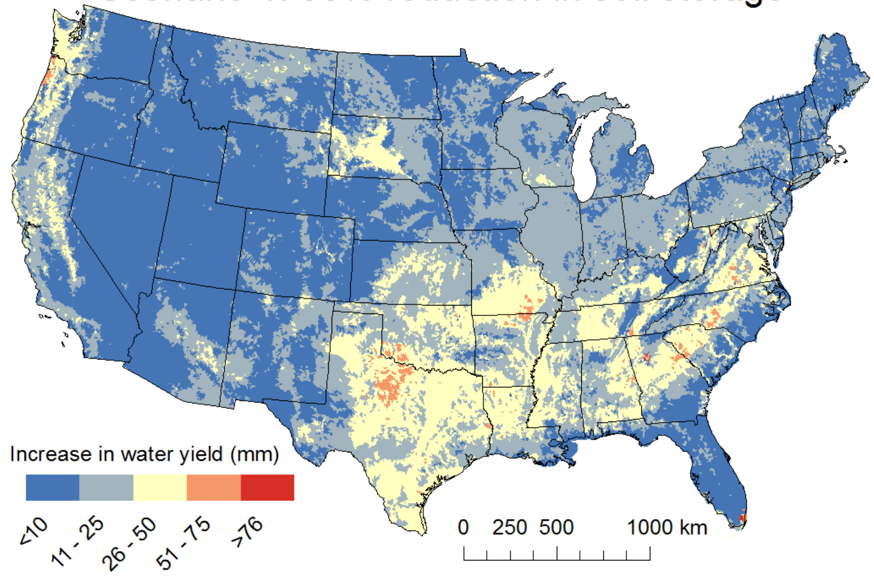
Reductions in soil water storage (scenario 1) resulted in smaller absolute increases in water yield than reductions in LAI (scenario 2), but larger relative increases, particularly in the Western U.S. regions (fig. 15 cf. fig. 14). The largest absolute increases in water yield associated with a reduction in soil water storage occurred in the South Atlantic-Gulf region (region 3) and along the Northwest Pacific coastal ranges (region 17). Reductions in LAI (scenario 2) resulted in larger absolute increases in water yield in the Eastern U.S. regions (water resource regions 1-9; fig. 16) but relative increases were smaller. In Western regions however, reductions in LAI resulted in small absolute increases (water resource regions 10-18) but larger relative increases, except along the Pacific Northwest (region 17) and upper elevations of the Rocky Mountains (region 14). These East-West differences reflect climate and vegetation patterns where precipitation, LAI, and water yield are generally higher in the East and lower in the West. Reductions in both soil water storage and LAI (scenario 3) reflected the combined effects of scenarios 1 and 2. Overall, water yield in the Eastern regions was more sensitive to decreases in LAI, and less sensitive to decreases in soil water storage, compared to the Western regions.

The 20% forest burn impact scenario (scenario 4) integrates our finding that at least one fifth of a watershed must be affected by fire to result in an appreciable effect on annual river flow (discussed in the section “Factors Contributing to Changes in River Flow”). Therefore, this scenario reflects the most likely burn conditions to cause a change in surface water yield. Absolute increases in water yield were low relative to other scenarios, but exhibited similar East-West spatial patterns as LAI and soil moisture storage decreased. The 20% forest burn impact scenario indicated that areas with large expected relative increases in water yield (+10% to +50%) include forests in the Columbia Mountains in Northeast Washington, in Northwestern Montana, Central Minnesota, Southern Utah and Colorado, the Black Hills in South Dakota, and Coastal Georgia-Northeast Florida.

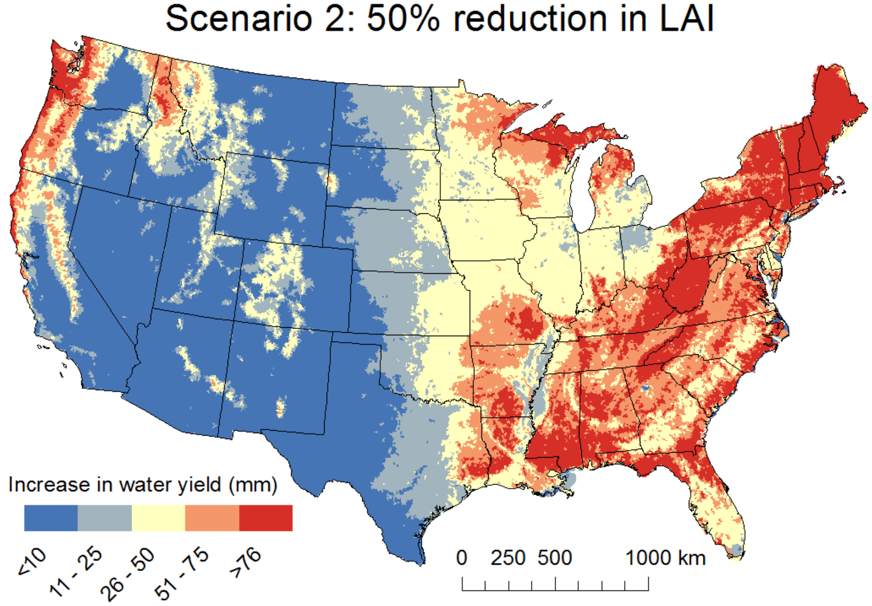
In the Eastern regions, absolute and relative increases in water yield due to the 20% forest burn were greatest in watersheds containing urban population centers with extensive impervious cover. In these watersheds, the undeveloped forested portion of the watershed represented the largest water loss through ET, because urbanized areas have low LAI and ET, and produce more surface runoff. As a result, these watersheds were more sensitive to changes in forest ET than others in the same hydroclimate with less urban and impervious cover. For example, HUC 031300020104 (Utoy Creek) near Atlanta, GA was 31% forested and 64% developed, with 45% of the developed land classified as impervious cover (29% of the entire watershed). The baseline July LAI for forest and urban land cover was 3.1 and 2.3, respectively, but the effective forest July LAI under the 20% burn scenario was reduced to 0.9 (-28%). Water yield under the baseline scenario was 547 mm yr^{-1}, but this increased to 782 mm yr^{-1} under the 20% forest burn scenario representing an increase of 234 mm yr^{-1} (43%).

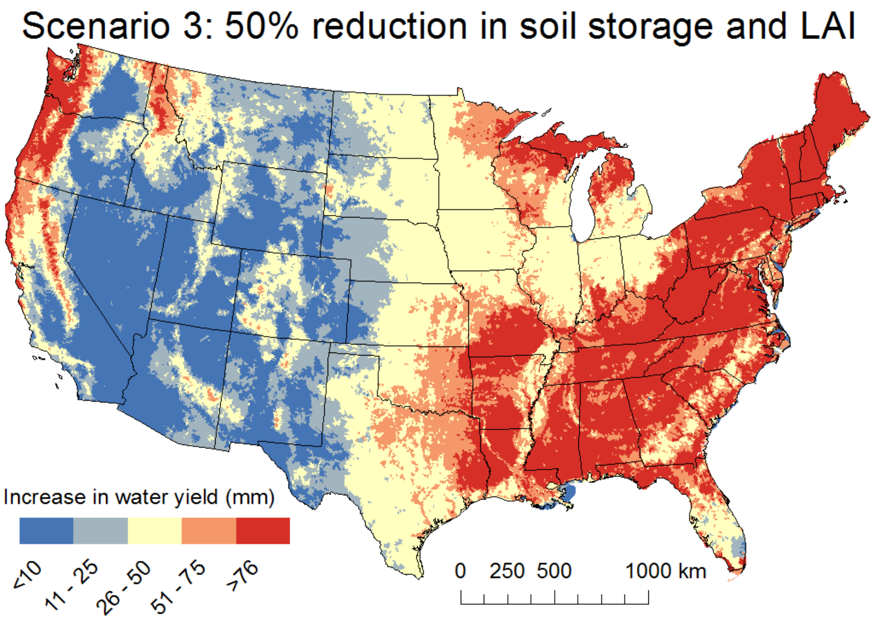
Across the CONUS, increases in water yield under this scenario were generally below +10%, suggesting that forest fires of this magnitude can potentially result in minor hydrologic effects. However, the increases in water yield under this burn impact scenario could be much larger in many watersheds depending on the combined effects of climate, soils, vegetation structure. Our model did not account for post fire rainfall intensity explicitly, even though short-duration high-intensity storms are an important trigger for post fire runoff on steep slopes (Williams and others 2014). While our empirical results showed some decreases in water yield (for example in Georgia) attributed to wildfire, the 20% burn scenario uniformly showed increases. The empirically derived predicted decreases were attributed to human activities and other disturbances (*e.g.*, hurricanes), factors not included in the modeling results. In this way, our simulations effectively isolated the potential impact of wildfires on water yield from these other factors.

Scenario 1: 50% reduction in soil storage



Scenario 2: 50% reduction in LAI





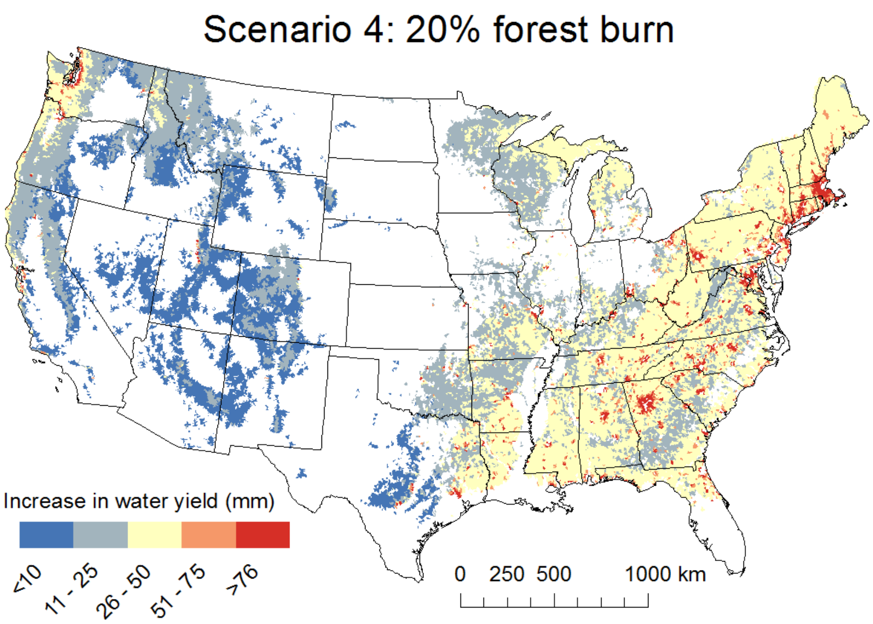
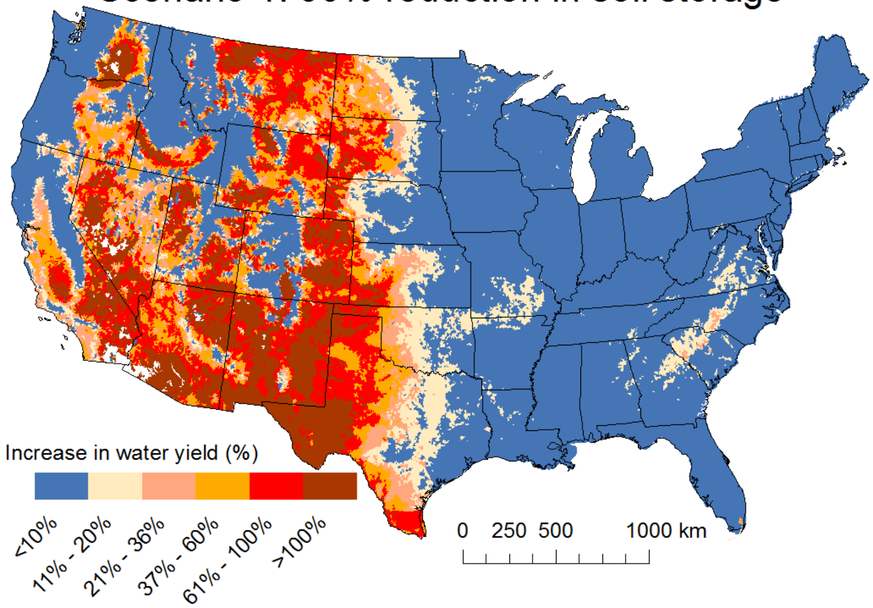
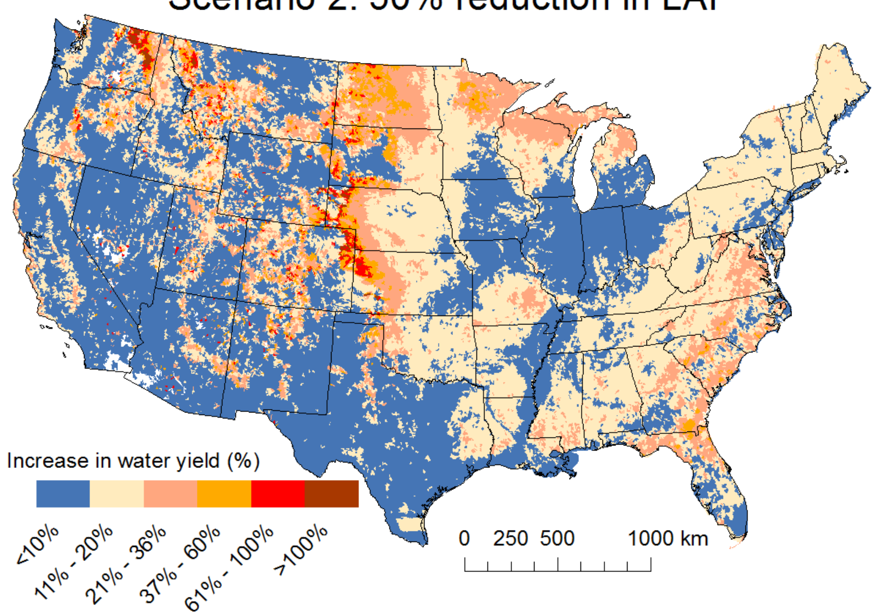


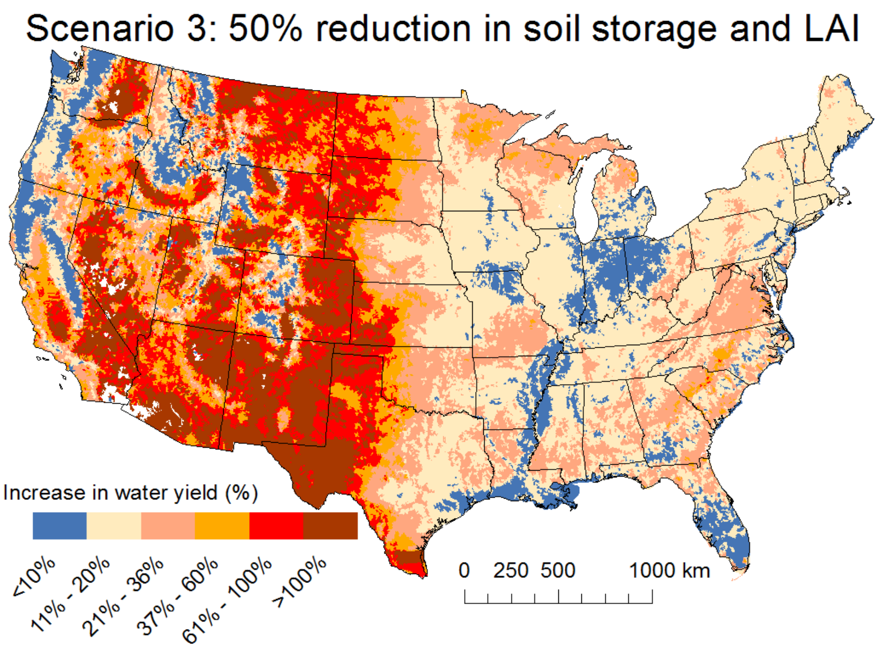
Figure 14. CONUS map showing absolute increases in total annual water yield (mm) under four hypothetical burn impact scenarios. Simulations performed with WaSSI at the HUC-12 watershed scale for the period between 2001 and 2010. Scenario 4 applies the minimum burned area threshold observed for impacts on river flow across 168 CONUS watersheds.

Scenario 1: 50% reduction in soil storage



Scenario 2: 50% reduction in LAI





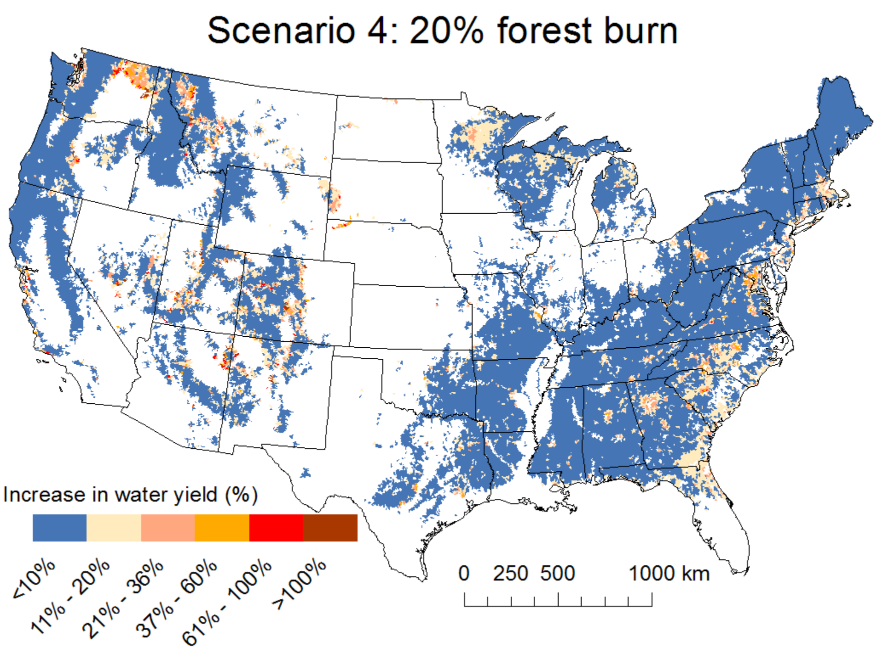


Figure 15. CONUS map showing relative increases in total annual water yield (mm) under four hypothetical burn impact scenarios. Simulations performed with WaSSI at the HUC-12 watershed scale for the period between 2001 and 2010. Scenario 4 applies the minimum burned area threshold observed for impacts on river flow across 168 CONUS watershed to those HUC-12 watersheds with greater than 20% forest cover.

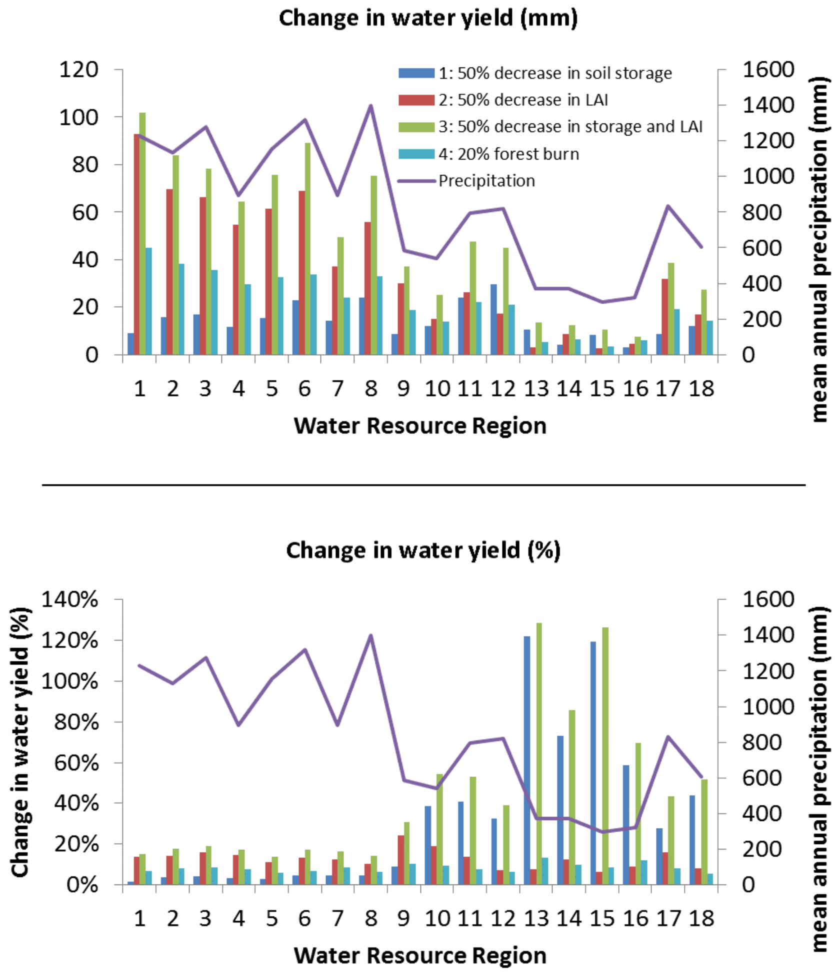


Figure 16. CONUS regional level comparison of the mean predicted absolute (top panel) and relative increase (bottom panel) in surface water yield for all HUC-12 watersheds under the four hypothetical burn scenarios.

FOREST MANAGEMENT IMPACTS

Fire-related management strategies are based on the understanding that most wildlands, including forests, are affected by fire sooner or later (Nunamaker and others 2007). The outcomes of these strategies vary depending on local conditions and on time. Therefore, land management decisions must account for expected responses to not only the fire impacts themselves but to all important factors—climate, vegetation structure, and human influence—and their interactions and effects over time (Jones and others 2018, Vira and others 2018).

For instance, pre-fire treatments such as prescribed burning and thinning aim to influence fire behavior by reducing the fuel load. When applied pro-actively over a long time frame, they can reduce fire impact risk by limiting the fire intensity and severity of burn impacts. Other management strategies deal with the susceptibility of the landscape to certain fire impacts. Surface treatments for example reduce erosion, and can be applied in both pre-fire treatment and post-fire strategies. In this section, we discuss the potential of fire-related management as a means to stabilize runoff and reduce the risk to surface freshwater supplies.

Prescribed Burning

Increased storm flow after large and severe wildfires can release pollutants like methyl-mercury, and represent a threat to the quality of surface water supplies. Fuel reduction treatments such as prescribed burning (fig. 17) have been suggested as a cost-effective measure to protect key water resource areas from extreme wildfires (Buckley and others 2014, Emelko and others 2011, Thompson and others 2013), and to promote the resilience of reforested sites (North and others 2018). With the increased use of low-severity prescribed burns, the question is how this affects the repartition of water in the landscape. The main water balance component affected is evapotranspiration.

For example, a prescribed burn may lead to a temporary reduction in stand evapotranspiration associated with a moderate loss of understory leaf area. Water use in New Jersey pitch pine was 27% lower immediately after a prescribed fire compared to an unburned control stand. After 30 days, water use was 11% to 25% higher compared to the control stand (Renniger and others 2013). The instantaneous intrinsic water use efficiency in the burned stand increased by 22% and carbon fixation increased more, suggesting that prescribed burning had initiated a change in physiology enabling the trees to decrease water use and increase water use efficiency (Renniger and others 2013).

Greater water use efficiency and reduced understory evapotranspiration suggest that prescribed burning can increase the water yield from burned areas. But evidence is limited to small-scale experimental studies. Our observations for 168 burned watersheds in the CONUS show no sign of surface water yield benefits ascribed *directly* to small, low severity prescribed burns, at scales larger than 10 km^2. The main reason, presented in this study, is that at least 20% of the vegetative cover must be removed to cause a significant change in river flow (Cawson and others 2012, Hallema and others 2017a, Hallema and others 2018a, Troendle and others 2010). Consequently, the *direct* impact of prescribed burns on water yield in larger basins is negligible compared to the direct effects of severe wildfires.

However, studies at smaller scaler have demonstrated *indirect* water supply benefits from prescribed burns in the East. Florida longleaf pine ecosystems burned every 2 to 5 years to maintain an open canopy, show evidence of increased water yield (McLaughlin and others 2013). However, this increased water yield is not the immediate result of prescribed burning, but of the lower basal area envisaged. This effect is most apparent at smaller scales. But even at smaller scales, interannual variations in climate and disturbances other than fire can affect the water yield. In another study in New Jersey, for example, no significant change could be linked to prescribed fire in a pitch pine (*Pinus rigida* L.) dominated stand that was also partially defoliated by gypsy moths (Clark and others 2012).

The extent, frequency and seasonal timing of prescribed burns affect potential benefits to water yield, and the duration of the effect. Effects on water yield are not expected to last beyond a few years—coincidentally the time between prescribed burns in the Southeast. Ecosystems with fire-adapted species, such as longleaf pine savanna in the Georgia coastal region, are burned approximately every two years in the winter or early spring. These stands experience a post-fire recovery of sensible heat, latent heat, and soil heat flux within 30 to 60 days after burning (Whelan and others 2015). But when conducted in the early spring, understory evapotranspiration is reduced in the summer that follows, potentially increasing the water yield until the next year.

Hydrological data from smaller watersheds support this theory—increased water yield has indeed been measured after prescribed burning in various locations across the Western United States (Robichaud 2000) and in New Jersey (increased recharge; Clark and others 2012). But direct evidence that prescribed burning is the cause of this phenomenon is still rare, and more research is needed on forest biomass-water yield interactions (Ahmed and others 2017). Regardless, studies convergence toward the understanding that the reduced risk of severe wildfires associated with large scale prescribed burning, can limit erosion problems in the long term, and contribute to a longer lifespan of reservoirs (Murphy and others 2018).

Coupled fire-water yield models, like the WaSSI adaptation presented in this report, can help evaluate 'what-if' scenarios to identify areas with potential benefits to water supplies, and areas eligible for priority treatment. This is critical, because to be sustainable from an economic viewpoint, the water protection benefits must outweigh the cost of prescribed burning operations and potential smoke hazard. Smoke development is an oft-cited argument against prescribed burn programs due to the inconvenience caused to nearby residents (Ozment and others 2016). Regardless, the city of Denver, Colorado, has used prescribed burning in its municipal watersheds since 2010, and serves as textbook example of prescribed burning in the wildland-urban interface.

Figure 17. Prescribed fire in the North Carolina Piedmont (Photo by Dennis W. Hallema, Southern Research Station).

Forest Thinning and Forest Restoration

Thinning is a common forest treatment involving the selective felling of trees from a forest stand to reduce the number of stems per area. The impact on water yield largely depends on the method of tree reduction, which is different for commercial thinning and non-commercial thinning. Commercial thinning helps to reduce tree competition for sunlight, water and nutrients, which improves forest productivity. Harvested trees are removed for the production of timber. Often, the skid trails and roads created during commercial thinning cause compaction of the ground surface and reduce its capacity to absorb water. This results in more storm runoff and increased sediment yield (Forsyth and others 2006, Luce and Black 1999, Robichaud and others 2010).

In contrast to commercial thinning, non-commercial thinning is applied as a pre-harvest fuel reduction treatment to reduce fire severity and promote forest restoration. The trees that are cut are left where they fall, and the nutrients contained within are recycled by the ecosystem. Selective non-commercial thinning of water-demanding tree species reduces forest vulnerability to fire by reducing evapotranspiration and drought stress at the stand scale, and increases water availability for ecosystems and humans (Grant and others 2013). Where commercial thinning generally reduces infiltration rates during heavy rainfall events, non-commercial thinning has a more subtle effect, if any, because it mainly affects evapotranspiration, not surface infiltration.

Most forest thinning operations are commercial, and—similar to wildfire impacts (Hallema and others 2018a)—will only increase annual water yield when more than 20% of the basal area of vegetation is removed (Bosch and Hewlett 1982, Stednick 1996). Estimates on the Kaibab Plateau in northern Arizona indicate that the restoration of mid-elevation spruce–fir, aspen, and mixed conifer forests, may be able to fully reverse the 10% decline in annual river flow expected based on climate-induced vegetation changes (O'Donnell and others 2018). Computational simulations in WaSSI for the Contiguous United States demonstrated that water yield can increase by 3%, 8%, and 13% when LAI is reduced by 20%, 50%, and 80%, respectively (Sun and others 2015b).

Surface Treatments

Pre-fire mulching is a mechanical treatment whereby woody fuel is shredded, ground, chunked, mowed or mulched, effectively rearranging vertical canopy fuels into horizontal fuels (Busse and others 2014). Mulch can contain wood shred or wood strands. Masticated fuels retain moisture longer (Kreye and others 2011), and help reduce the susceptibility of fuels for ignition, fire rate of spread and fire intensity (Stephens and others 2009). Mulching also increases perennial grass cover, thereby mitigating erosion and increasing water availability. For example, rainfall simulations on a piñon juniper rangeland in Utah showed reduced high levels of runoff (40-45 mm) by 4 to 5 fold (10 mm) after mulching (Pierson and others 2014). Similar effects have been observed in sagebrush communities in the Great Basin and the Colorado Plateau in springtime (Roundy and others 2014, Young and others 2013).

Post-fire mulching also reduces runoff from burned hillslopes. If the canopy is burned by fire, a mulch layer can protect the soil surface against the direct impact of rainfall. This reduces the likelihood of surface compaction and infiltration issues (Stottlemyer and others 2015), with less runoff and erosion problems as a result (Cline and others 2010, Groen and Woods 2008). No negative effects on forest recovery have been reported (Dodson and Peterson 2010). Hydromulching is an effective erosion control treatment that involves the spraying of a mixture of water, fiber mulch, and tackifier. But it is expensive, and the high cost limits its use to severely burned areas in steep terrain (Hubbert and others 2011). Cheaper forms of mulch, in particular straw mulch, are also effective and frequently applied in hillslope stabilization treatments following severe wildfire.

For example, a study in burned Douglas-fir stands in the Rocky Mountains (Idaho, southeast Washington and Colorado) recommends a total ground cover of at least 60% with wood strand and straw mulch. This combination reduced runoff and sediment yield during at least one year after wildfires (Robichaud and others 2013a). Wheat straw mulch application reduced peak flow and sediment yield after the 2002 Hayman Fire site in central Colorado, with annual peak flow rates of 4.5 and 3.9 $m^3.s^{-1}.km^{-2}$, respectively, in post-fire years one and two in the straw mulch catchment vs. 4.3 and 7.1 $m^3.s^{-1}.km^{-2}$ in the control catchment (Robichaud and others 2013b). The straw mulch catchment produced no runoff or sediment after the second post-fire year, while the control catchment continued to generate runoff and sediment through the seventh year after the fire.

Despite the lack of conclusive evidence for a link between the reestablishment of vegetation and runoff during the first year after a fire (Beyers 2004, Peppin and others 2010, Robichaud and others 2000, Wagenbrenner and others 2006), grass seeding is a popular and inexpensive post-fire treatment in many western regions. The natural vegetation recovery in the first post-fire year, is often insufficient to mitigate runoff and erosion. Ground cover is typically low compared to hillslopes treated with mulching, 5% vs. nearly 100% in the case of a treatment in northwest Montana (Groen and Woods 2008). On that site, the naturally regenerated vegetative cover proved insufficient to reduce rain splash erosion, however mulching reduced rain splash erosion by 87%.

Salvage Logging

Research on the effects of post-fire salvage logging on surface hydrology in the U.S. is limited (Leverkus and others 2018). As such, we provide examples from research sites outside of the U.S. to gain insight into their potential impacts on water yield. For example, the 2003 Lost Creek fire affected a forest with Lodgepole pine, trembling aspen, and Subalpine fir on the east slope of the Rocky Mountains in Alberta, Canada. A study on seven watersheds affected by this fire showed that the mean timing of the onset of spring melt occurred approximately 2 to 3 weeks earlier in salvage logged watersheds, compared to those that were only burned. However, the average magnitude of peak snowmelt discharge was lower in the salvage logged catchment compared to the burned catchments (*i.e.*, 2.4 mm vs. 5.5 mm; Wagner and others 2014).

The physical controls for this response are not well understood. But, it is generally assumed that changes in surface cover and soil properties due to salvage logging operations have a greater effect on post-fire peak flows and hillslope erosion than the loss of vegetative evapotranspiration (Shakesby and Doerr 2006). Wagenbrenner and others (2015) obtained data from four sites in Colorado, Montana and north-central Washington, and confirmed that the skid trails and feller-buncher plots in salvage-logged plots had greater compaction and less soil water repellency than on the control plots. The skidder plots produced 10 to 100 times more sediment than the control plots, and the feller-buncher plot produced only 10% to 30% more sediment. The difference with the control plots increased with time because vegetative regrowth was faster on the control plots. The compaction of logged plots increased sediment production, although no significant effects on total runoff were observed (Wagenbrenner and others 2015).

Still, there is little consensus on whether post-fire timber harvest mitigates or exacerbates the effects of wildfire on regrowth, surface runoff, erosion and soil water repellency (Peterson and others 2009). One of the difficulties in assessing salvage logging impact on hydrology is that the collateral effects of logging overlap with hydrologic disturbance caused by the fire. This is indicative of the general challenges with disentangling the hydrologic effects of overlapping disturbances (Ebel and Mirus 2014, Hallema and others 2018a), and makes it difficult to separate causes and effects of hydrologic responses to fire (Wagenbrenner and others 2015).

DISCUSSION

The impact of wildland fires on surface water supplies has received more public attention in recent years (Bladon and others 2014, Smith and others 2011). Much of this attention pertains to concerns about fire impacts on the quality of water used for irrigation and drinking, and the increased cost of water treatment to ensure that even after a wildfire, water quality poses no threat to public health (Hohner and others 2016, Writer and others 2014). Many studies have focused on mountain headwaters in the months immediately following wildfire, where water supplies can degrade rapidly as result of increased risk of surface runoff and erosion during rainstorms, and where destructive flash floods and debris flows are common after wildfire (Cannon and others 2008, Moody and Martin, 2001).

Research into wildland fire impacts on water supplies at larger scales has only recently gained momentum (Hallema and others 2017a, Hallema and others 2018a, Saxe and others 2018, Wine and others 2018). But to our knowledge, this study is the first to investigate wildland fire impacts on water yield across the entire Contiguous United States. The climate elasticity approach combined with the Machine Learning program we developed helped identify the climate, wildland fire, topographical, and land cover variables with the greatest influence on annual river flows from burned watersheds. This further enabled us to detect environmental thresholds for impact on annual river flow with great accuracy, and allowed us to avoid the assumptions of many computational models, and the cross-correlation issues that would result from applying the Budyko equations at this scale.

Our findings and modeling tools provide new insights into large scale interactions between climate, fire, topography and land cover, and characterize the regional vulnerability of surface water supplies. They show that areas with severe burn impacts contribute more to annual river flow than area with low burn impacts. Limiting wildfire risk to water quality through appropriate forest management is a critical endeavor. The assessment presented in this report gives practical information for source water protection programs, and is useful in weighing the potential impacts of severe wildfires against those of prescribed fires in municipal watersheds located within forested headwaters. Even so, the increased post-fire annual water yield we detected in many regions are not automatically beneficial to hydrological services (Hallema and others 2018b).

For example, many large metropolitan areas are able to treat surface water of limited quality in a cost-effective manner. However, the cost-efficiency of water production is highly dependent on a continuous volume supply with limited tolerance for variations in water quality (House-Peters and Chang, 2011), even if the water quality complies with Clean Water Act standards at all times. The continuity of water supply is a challenge in fire-affected watersheds, because fire can alter the timing and magnitude of river flow (Bart and Tague 2017, Kinoshita and Hogue 2015, Lanini and others 2009). The expected increase in climate extremes will make water supply forecasting more challenging in the future (Mirus and others 2017, Moody and Martin, 2004).

CONCLUSIONS

CONUS flow records for 168 burned watersheds from the past 30 years show that annual river flow coming from burned watersheds increased most in the Lower Mississippi, Lower and Upper Colorado water resource regions. In contrast, the greatest decrease in river flow was observed in the Great Basin, Rio Grande, Texas-Gulf, and California regions. Wildland fire enhanced observed river flow in Southern California, even though this impact was often masked by declining trends in precipitation resulting in a net decrease in river flow.

Fire impacts were greatest in the Lower Colorado and Pacific Northwest regions (>+100% increase in river flow), especially in Arizona where watersheds were burned over more than one half of their area. In Northern California and in the Missouri region, river flow declined mainly as a result of climate variability, and wildland fire impacts on annual river flow appear minimal (<+50% increase in river flow). The influence of areas with high or moderate burn severity impacts, on the change in annual river flow, is secondary to the effect of interannual variations in climate.

We have also shown that wildfires and prescribed fires affecting less than 20% of a basin are unlikely to produce any lasting effects on annual river flow in basins larger than 10 km^2. While prescribed burns are too limited in extent and severity, to affect annual river flow directly, our results do not exclude the possibility of an indirect effect in landscapes where prescribed burning is used to maintain a low basal area. Data on larger prescribed fires are needed to properly assess their benefit for water management plans.

Our observations in 168 burned watershed and physically-based distributed hydrologic simulations of potential burn impacts for 88,000 HUC-12 level watersheds in all regions of the CONUS, demonstrate that wildland fire impacts vary regionally. Wildfires and drought can cause a compound effect on annual river flow resulting in more extreme water yield during post-fire years, or conversely, cancel each other out partially in regions like California. These variations in response underline the importance of integrating the current knowledge into resources management, and emphasize the need to tailor post-wildland fire management to the local needs in each region.

Future watershed-level fire-hydrology studies need to examine hydrologic variables beyond mean annual streamflow such as peakflow and lowflows that are also closely related to aquatic ecosystem functions. Process-based studies are needed to move beyond a ‘black box’ approach to examine how ecosystem structure (leaf area index, plant species change) and soil dynamics (change in soil physical properties) affect watershed hydrology. Ecohydrological models need to be validated with streamflow and other hydrologic fluxes such as evapotranspiration and soil moisture derived from in-situ measurements and remote sensing.

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APPENDIX A: DESCRIPTION OF CLIMATE TYPE

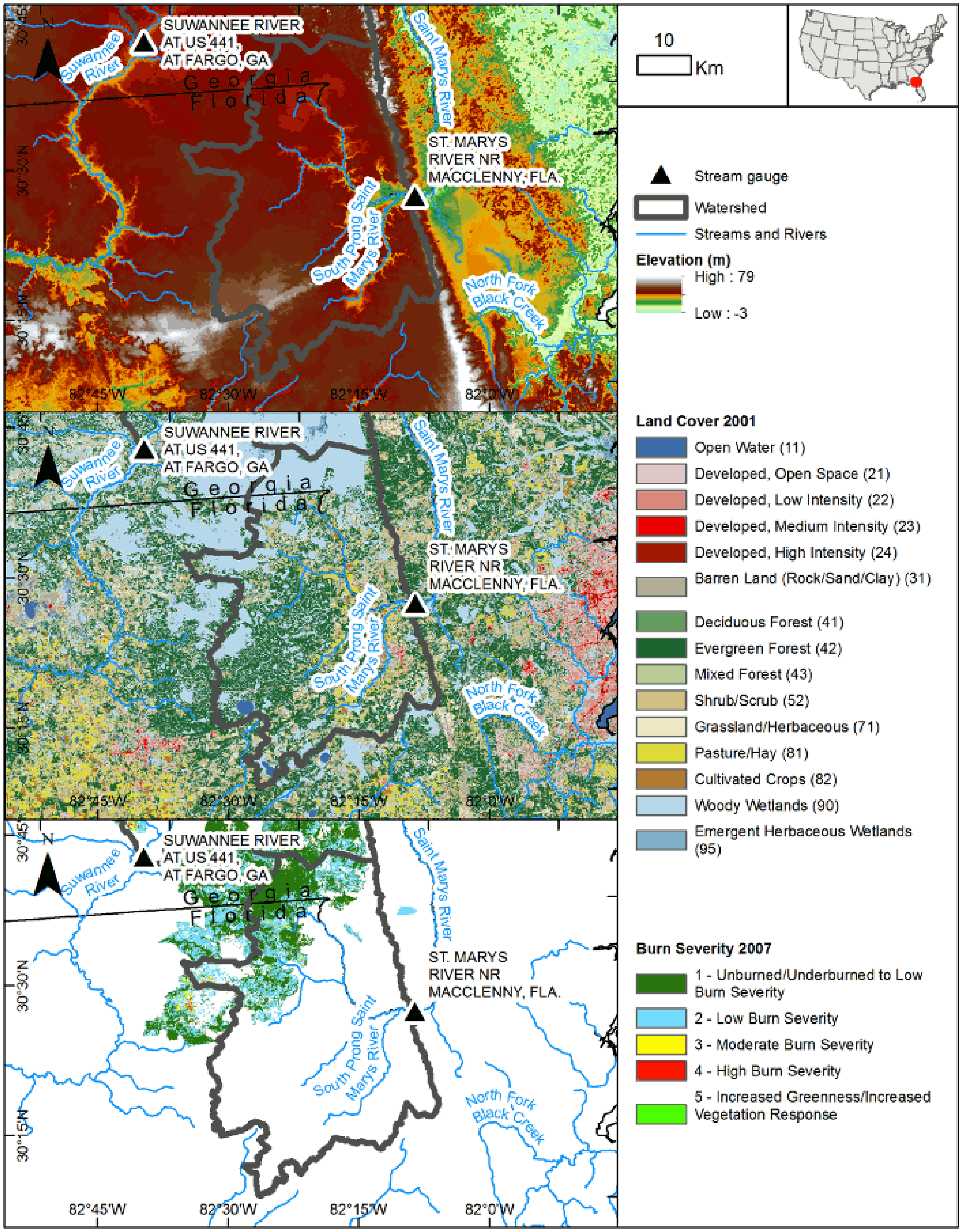
Supplementary Table 1. Description of Köppen climate symbols and defining criteria (Peel and others 2007).

1st	2nd	3rd	Description	Criteria*
A			Tropical	$T_{cold} \geq 18$
	f		- Rainforest	$P_{dry} \geq 60$
	m		- Monsoon	Not (Af) & $P_{dry} \geq$ 100-MAP/25
	w		- Savannah	Not (Af) & $P_{dry} <$ 100-MAP/25
B			Arid	MAP < 10 × $P_{threshold}$
	W		- Desert	MAP < 5 × $P_{threshold}$
	S		- Steppe	MAP ≥ 5 × $P_{threshold}$
		h	- Hot	MAT ≥ 18
		k	- Cold	MAT < 18
C			Temperate	$T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Cs) or (Cw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a or b) & $1 \leq T_{mon10} < 4$
D			Cold	$T_{hot} > 10$ & $T_{cold} \leq 0$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a, b or d)
		d	- Very Cold Winter	Not (a or b) & $T_{cold} < -38$
E			Polar	$T_{hot} < 10$
	T		- Tundra	$T_{hot} > 0$
	F		- Frost	$T_{hot} \leq 0$

*MAP = mean annual precipitation, MAT = mean annual temperature, T_{hot} = temperature of the hottest month, T_{cold} = temperature of the coldest month, T_{mon10} = number of months where the temperature is above 10°C, P_{dry} = precipitation of the driest month, P_{sdry} = precipitation of the driest month in summer, P_{wdry} = precipitation of the driest month in winter, P_{swet} = precipitation of the wettest month in summer, P_{wwet} = precipitation of the wettest month in winter, $P_{threshold}$ = varies according to the following rules (if 70% of MAP occurs in winter, then $P_{threshold}$ = 2 × MAT; if 70% of the MAP occurs in summer, then $P_{threshold}$ = 2 × MAT + 28, otherwise $P_{threshold}$ = 2 × MAT + 14). Summer (winter) is defined as the warmer (cooler) six month period of ONDJFM and AMJJAS.

APPENDIX B: WATERSHED MAPS AND TABULAR DATA

St. Marys River near MacClenny, Florida (Gauge 2231000)/2007 Big Turnaround Complex Wildfire



St. Marys River near MacClenny, Florida

Water Resource Region: South-Atlantic-Gulf (HUC-2 code 3) Climate Type (Köppen): Cfa

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
2231000	30.358847 N	82.081501 E	1748.4	1.80

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
16	66	39	4.0	0.3

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	37%	1%	5%	3%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
12%	36%	1%	5%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Big Turnaround Complex	4/25/2007	Wildfire	337.8	19.3%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
10.6%	8.4%	0.2%	0.0%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1499	1287	-212	-14.1

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	0	0	0	0.0

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	7538	6881	-657	-8.7

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	1137	1136	-1	-0.1

River Flow (5 Years Before and After Wildland Fire)

Annual River Flow

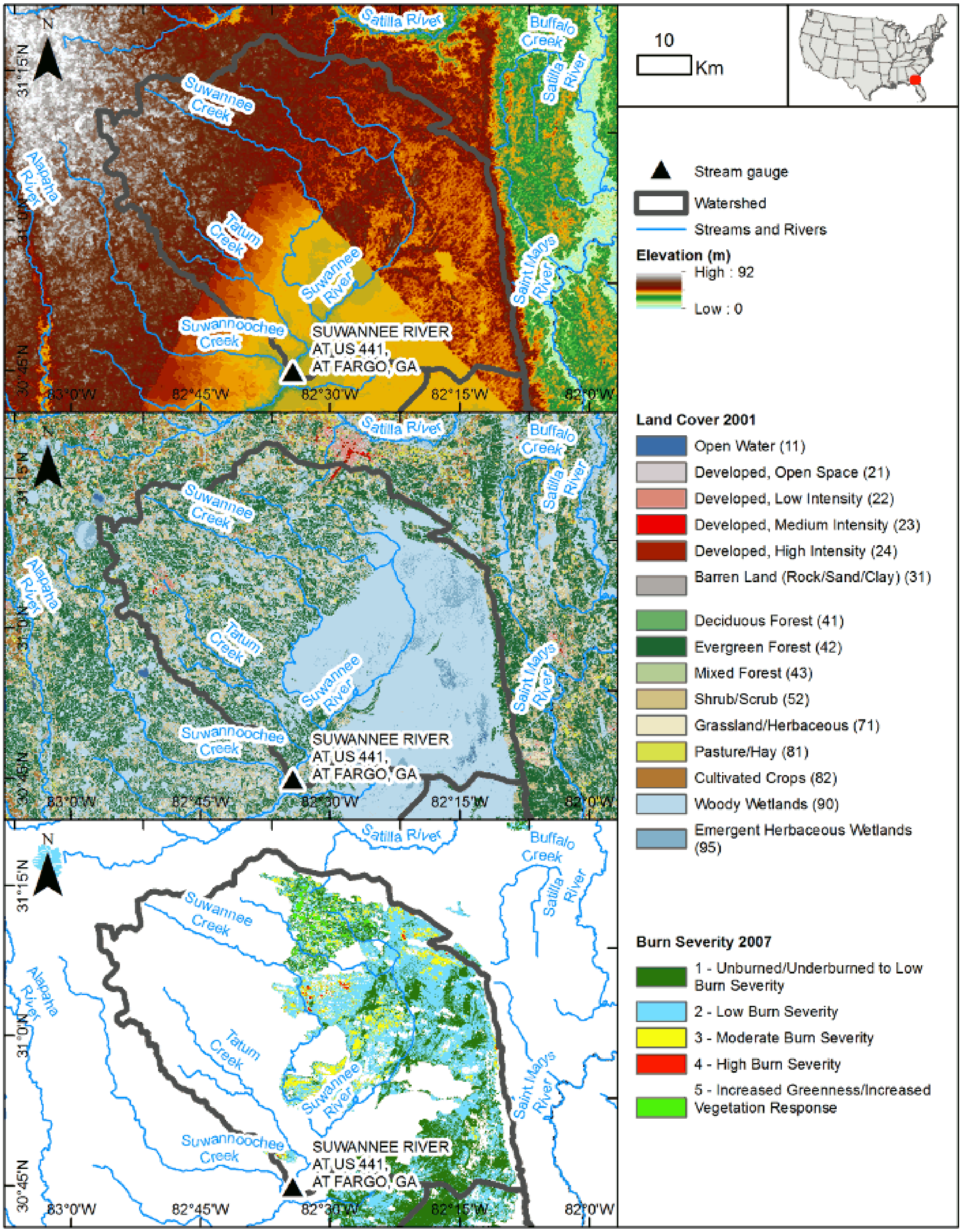
Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	333	177	-156	-46.9

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM2*	-31.4	-124.7*	-9.4	-37.5*

*River flow may be influenced by drought impacts on baseflow, which are not accounted for.

Suwannee River at Fargo, Georgia (Gauge 2314500)/2007 Sweat Farm Road Wildfire



Suwannee River at Fargo, Georgia

Water Resource Region: South-Atlantic-Gulf (HUC-2 code 3) — Climate Type (Köppen): Cfa

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km²)*	*Shape Parameter*
2314500	30.680556	-82.560556	3322.2	1.39

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
30	78	47	4.2	0.6

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	22%	0%	4%	1%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
7%	63%	0%	3%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km²)*	*Burned Area to Drainage Area Ratio (%)*
Sweat Farm Road	4/16/2007	Wildfire	1252.9	37.7%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
13.1%	21.4%	3.1%	0.1%	0.7%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1403	1237	-166	-11.8

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	0	0	0	0.0

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	6998	4477	-2521	-36.0

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	1116	1115	-1	-0.1

River Flow (5 Years Before and After Wildland Fire)

Annual River Flow

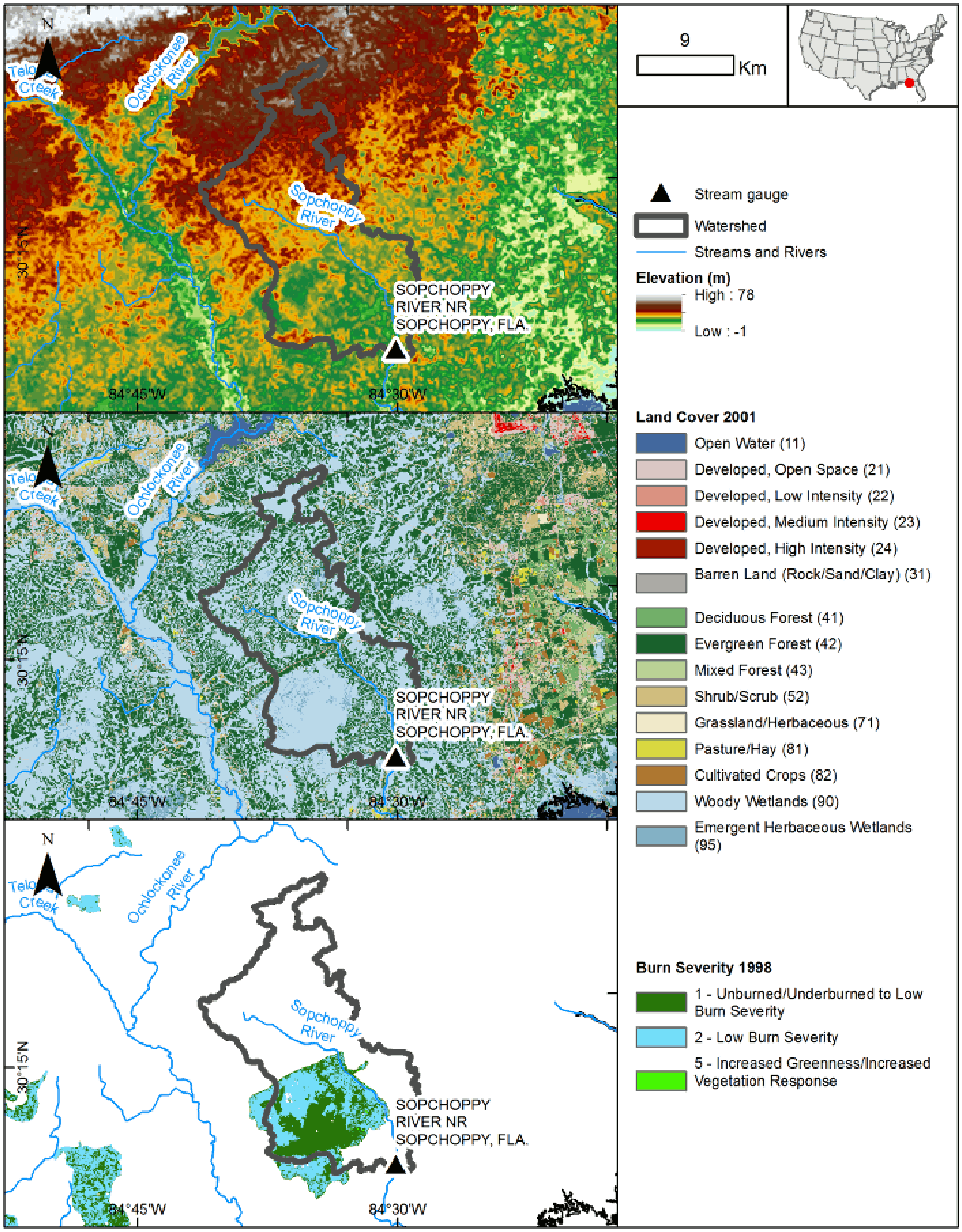
Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	239	111	-127	-53.3

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM4*	-20.8	-106.5*	-8.7	-44.6*

*River flow may be influenced by drought impacts on baseflow, which are not accounted for.

Sopchoppy River near Sopchoppy, Florida (Gauge 2327100)/1998 Holiday Wildfire



Sopchoppy River near Sopchoppy, Florida

Water Resource Region: South-Atlantic-Gulf (HUC-2 code 3) Climate Type (Köppen): Cfa

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
2327100	30.129369 N	84.494348 E	271.1	1.95

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
17	55	31	3.2	0.7

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	32%	0%	1%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
1%	64%	0%	2%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Holiday	5/25/1998	Wildfire	81.0	29.9%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
15.8%	14.1%	0.0%	0.0%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1615	1406	-209	-12.9

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	0	0	0	0.0

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	5217	10306	5090	97.6

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	1084	1111	28	2.6

River Flow (5 Years Before and After Wildland Fire)

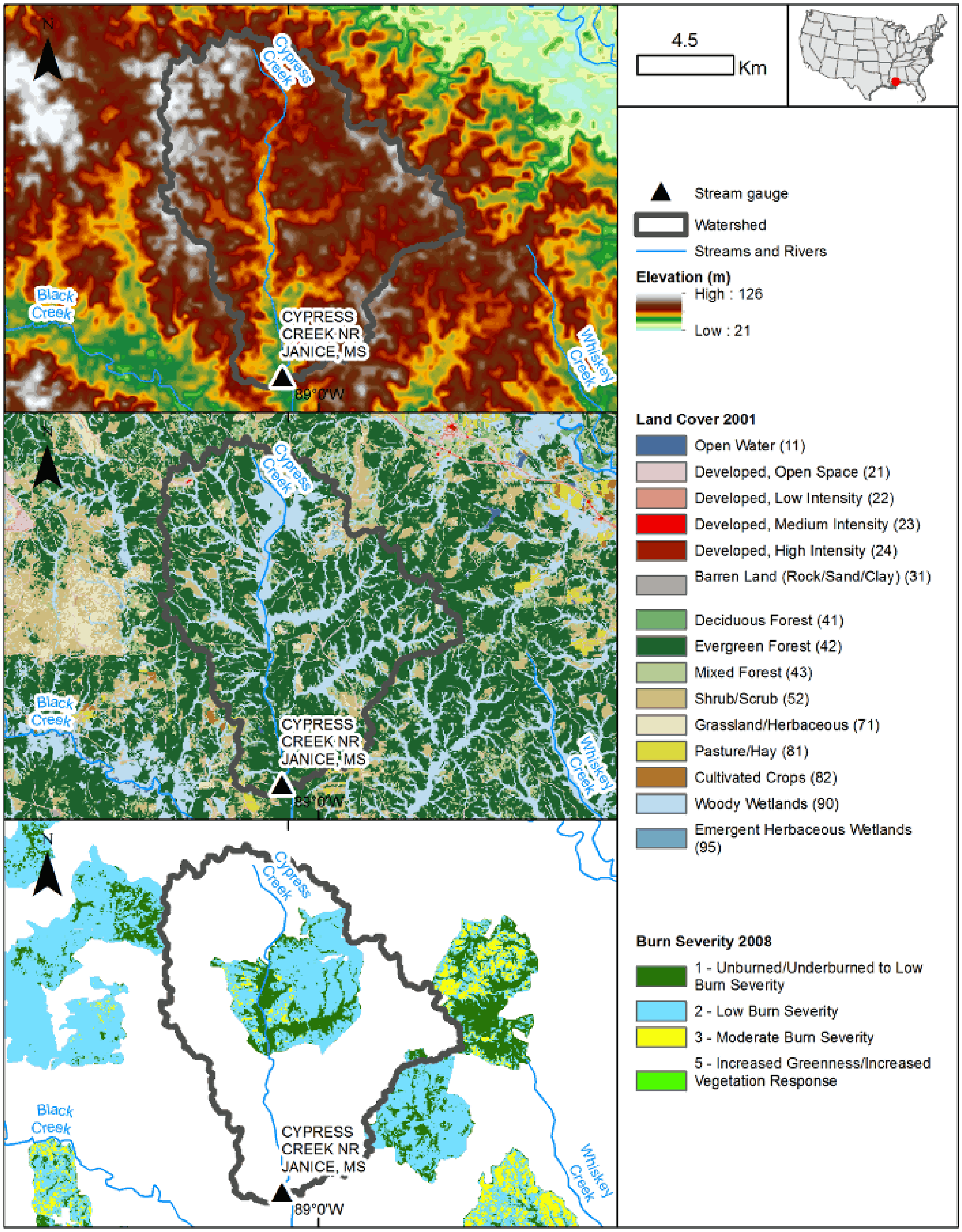
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	629	586	-43	-6.8

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM2	-27.8	-15.1	-4.4	-2.4

Cypress Creek near Janice, Mississippi (Gauge 2479155)/2008 Unnamed Prescribed Fire



Cypress Creek near Janice, Mississippi

Water Resource Region: South-Atlantic-Gulf (HUC-2 code 3) — Climate Type (Köppen): Cfa

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
2479155	31.025278 N	89.016667 E	137.3	1.91

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
50	114	80	4.9	1.6

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	56%	6%	1%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
8%	24%	0%	4%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Unnamed	3/16/2008	Prescribed Fire	33.2	24.1%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
6.9%	16.9%	0.4%	0.0%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1558	1734	176	11.3

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	0	0	0	0.0

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	7395	8711	1316	17.8

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	1084	1094	10	1.0

River Flow (5 Years Before and After Wildland Fire)

Annual River Flow

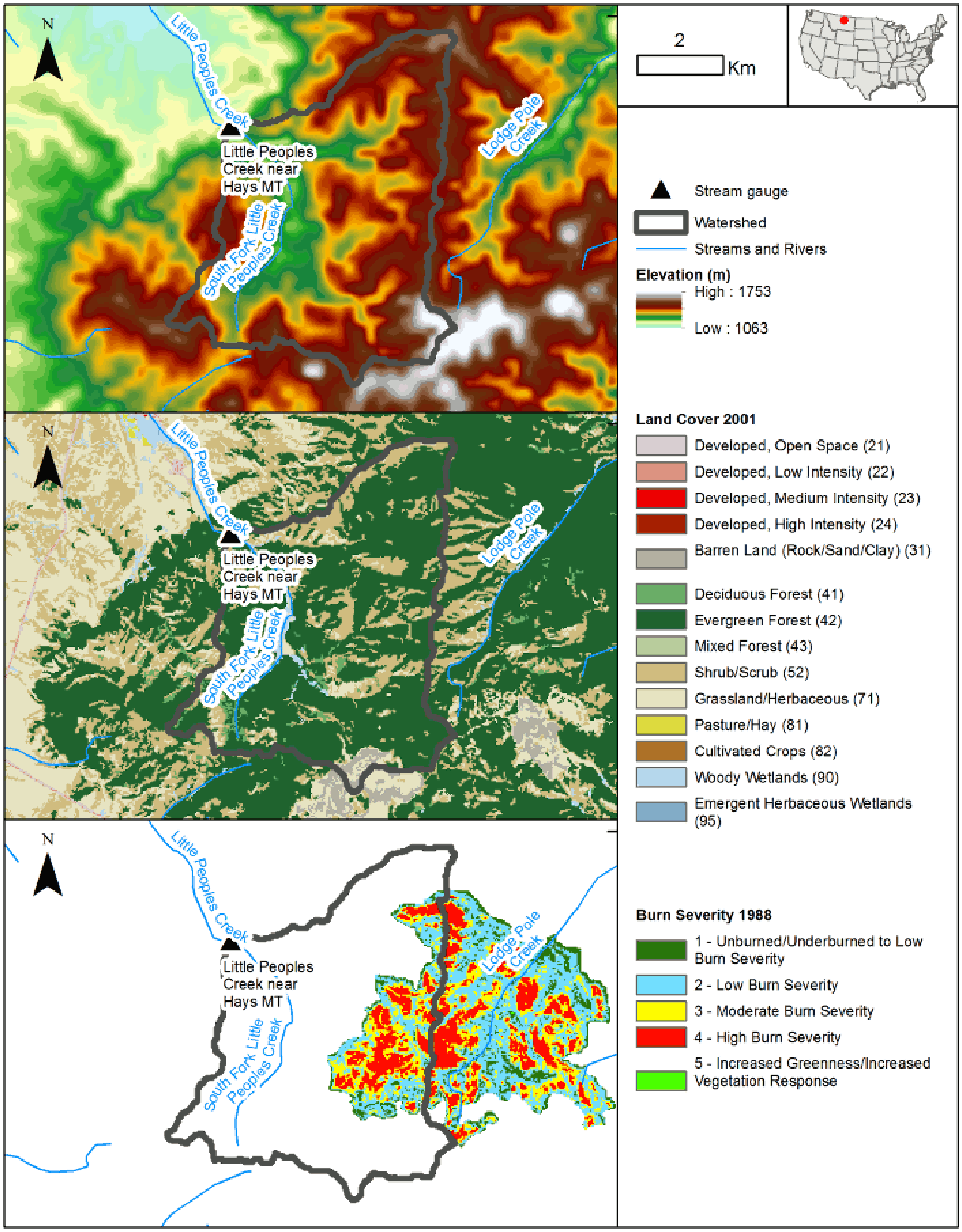
Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	521	536	15	2.9

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM2	-52.1	67.2*	-10.0	12.9*

*River flow is also influenced by the effects of Hurricane Katrina (2005), which are not accounted for.

Little People's Creek near Hays, Montana (Gauge 6154410)/1988 Monument Wildfire



Little Peoples Creek near Hays, Montana

Water Resource Region: Missouri (HUC-2 code 10) | Climate Type (Köppen): BSk

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
6154410	47.966104 N	108.66071 E	33.4	1.75

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
1192	1689	1384	32.5	13.6

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
3%	68%	0%	5%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
21%	2%	0%	0%	1%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Monument	7/22/1988	Wildfire	7.8	23.3%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
3.1%	8.4%	5.7%	6.1%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	540	516	-24	-4.5

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	6016	4222	-1794	-29.8

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1953	2502	549	28.1

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	565	565	0	0.0

River Flow (5 Years Before and After Wildland Fire)

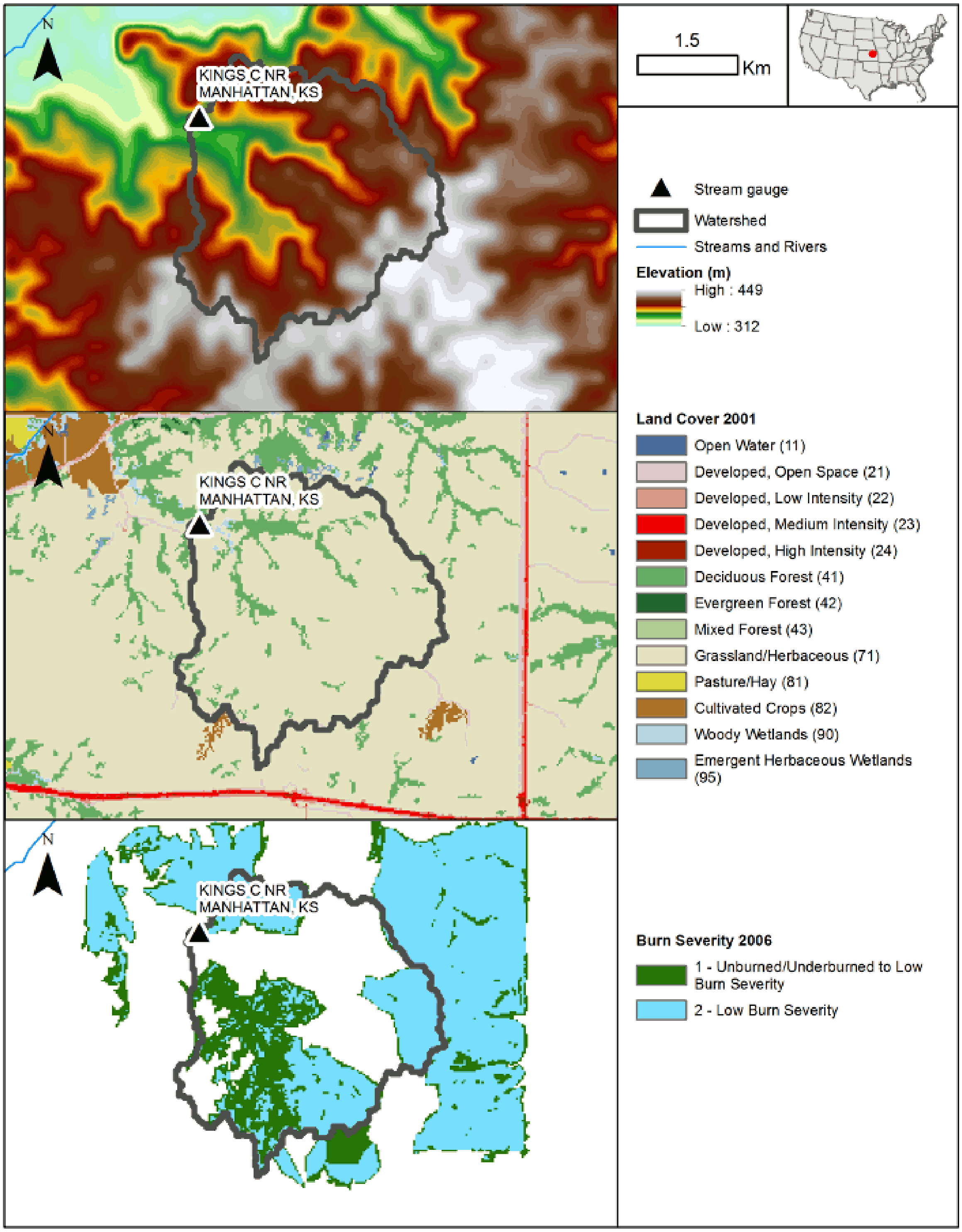
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	99	93	-7	-6.8

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM4	8.0	-14.7	8.0	-14.8

Kings Creek near Manhattan, Kansas (Gauge 6879650)/2006 Unnamed Fire



King's Creek near Manhattan, Kansas

Water Resource Region: Missouri (HUC-2 code 10) Climate Type (Köppen): Dfa

Gage Number	Latitude	Longitude	Drainage Area (km^2)	Shape Parameter
6879650	39.101948 N	96.595214 E	11.5	1.72

Topography (GMTED2010)

Lowest Elevation (m)	Highest Elevation (m)	Mean Elevation (m)	Maximum Slope (%)	Mean Slope (%)
347	439	397	9.6	4.2

Land Cover (NLCD 2001)

Deciduous Forest	Evergreen Forest	Mixed Forest	Grassland-Herbaceous	Cultivated Crop
8%	0%	0%	91%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
0%	1%	0%	1%	0%

Wildland Fire (MTBS)

Name	Date	Type	Burned Area (km^2)	Burned Area to Drainage Area Ratio (%)
Unnamed	4/22/2006	Unknown	7.6	65.6%

Unburned-Underburned	Low Severity	Moderate Severity	High Severity	Increased Greenness
33.5%	32.1%	0.0%	0.0%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
Daymet	928	1067	139	15.0

Annual Snow Water Equivalent

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
Daymet	638	1773	1135	177.7

Monthly Precipitation Variance

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
Daymet	4048	5417	1369	33.8

Annual Potential Evapotranspiration

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
PRISM	856	827	-28	-3.3

River Flow (5 Years Before and After Wildland Fire)

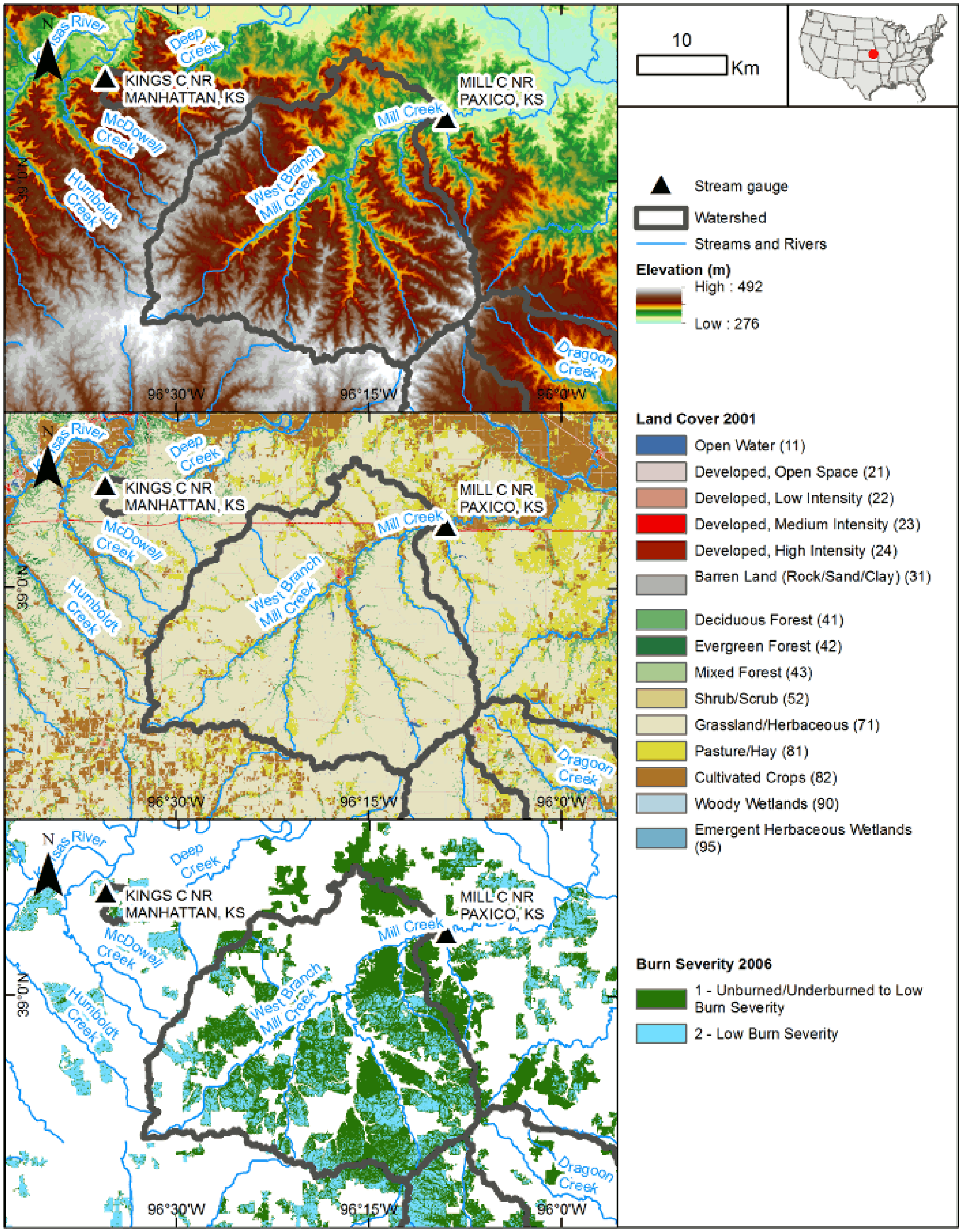
Annual River Flow

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
GAGES-II	76	130	54	70.9

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	Change Attributed to Climate (mm)	Change Attributed to Wildland Fire (mm)	Change Attributed to Climate (%)	Change Attributed to Wildland Fire (%)
CEM3	52.6	1.2	69.4	1.6

Mill Creek near Paxico, Kansas (Gauge 6888500)/2006 Unnamed Fire



Mill Creek near Paxico, Kansas

Water Resource Region: Missouri (HUC-2 code 10) — Climate Type (Köppen): Dfa

Gage Number	Latitude	Longitude	Drainage Area (km^2)	Shape Parameter
6888500	39.062655 N	96.150252 E	842.3	1.96

Topography (GMTED2010)

Lowest Elevation (m)	Highest Elevation (m)	Mean Elevation (m)	Maximum Slope (%)	Mean Slope (%)
303	489	400	13.6	3.0

Land Cover (NLCD 2001)

Deciduous Forest	Evergreen Forest	Mixed Forest	Grassland-Herbaceous	Cultivated Crop
4%	0%	0%	78%	13%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
0%	0%	0%	3%	0%

Wildland Fire (MTBS)

Name	Date	Type	Burned Area (km^2)	Burned Area to Drainage Area Ratio (%)
Unnamed	2/22/2006	Unknown	509.1	60.5%

Unburned-Underburned	Low Severity	Moderate Severity	High Severity	Increased Greenness
46.1%	14.3%	0.0%	0.0%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
Daymet	965	986	20	2.1

Annual Snow Water Equivalent

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
Daymet	815	2327	1512	185.5

Monthly Precipitation Variance

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
Daymet	3920	3455	-465	-11.9

Annual Potential Evapotranspiration

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
PRISM	825	811	-14	-1.6

River Flow (5 Years Before and After Wildland Fire)

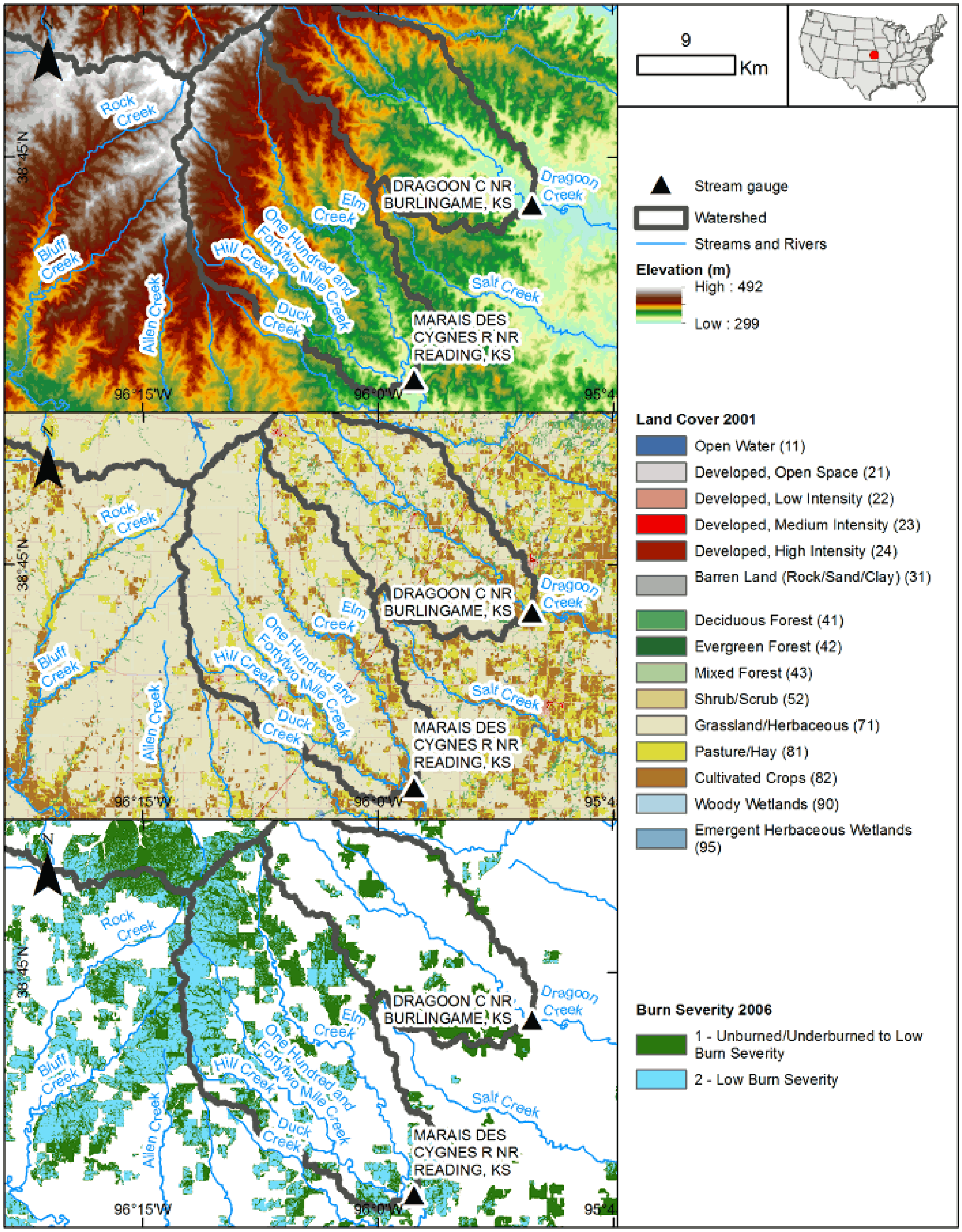
Annual River Flow

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
GAGES-II	174	213	39	22.7

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	Change Attributed to Climate (mm)	Change Attributed to Wildland Fire (mm)	Change Attributed to Climate (%)	Change Attributed to Wildland Fire (%)
CEM3	25.4	13.9	14.6	8.0

Marais des Cygnes River near Reading, Kansas (Gauge 6910800)/2006 Unnamed Fire



Marais des Cygnes River near Reading, Kansas

Water Resource Region: Missouri (HUC-2 code 10) Climate Type (Köppen): Dfa

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
6910800	38.567005 N	95.961632 E	444.6	1.92

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
327	479	390	5.1	1.6

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
3%	0%	0%	70%	22%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
0%	1%	1%	3%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Unnamed	2/22/2006	Unknown	242.7	54.6%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
29.7%	24.9%	0.0%	0.0%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	974	1031	57	5.8

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	889	1909	1020	114.7

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	3925	3181	-743	-18.9

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	825	823	-2	-0.2

River Flow (5 Years Before and After Wildland Fire)

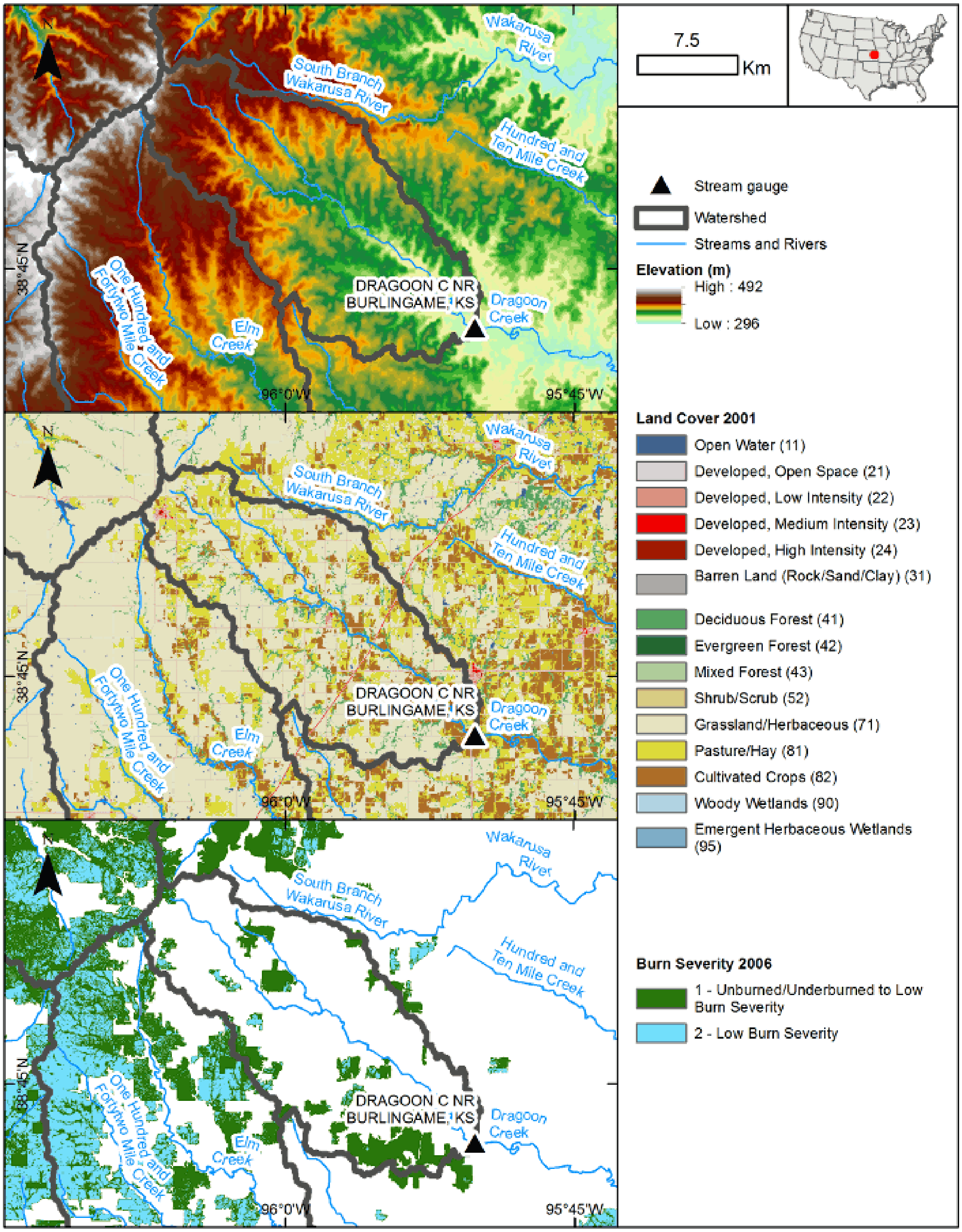
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	187	230	43	22.7

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM3	9.4	33.1	5.0	17.7

Dragoon Creek near Burlingame, Kansas (Gauge 6911900)/2006 Unnamed Fire



Dragoon Creek near Burlingame, Kansas

Water Resource Region: Missouri (HUC-2 code 10) Climate Type (Köppen): Dfa

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
6911900	38.71069 N	95.836029 E	293.1	1.95

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
318	477	371	6.2	1.7

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
6%	0%	0%	54%	34%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
0%	1%	0%	5%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Unnamed	4/22/2006	Unknown	66.3	22.6%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
21.1%	1.6%	0.0%	0.0%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	991	1033	41	4.2

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	891	1808	918	103.0

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	3857	3192	-666	-17.3

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	827	822	-5	-0.6

River Flow (5 Years Before and After Wildland Fire)

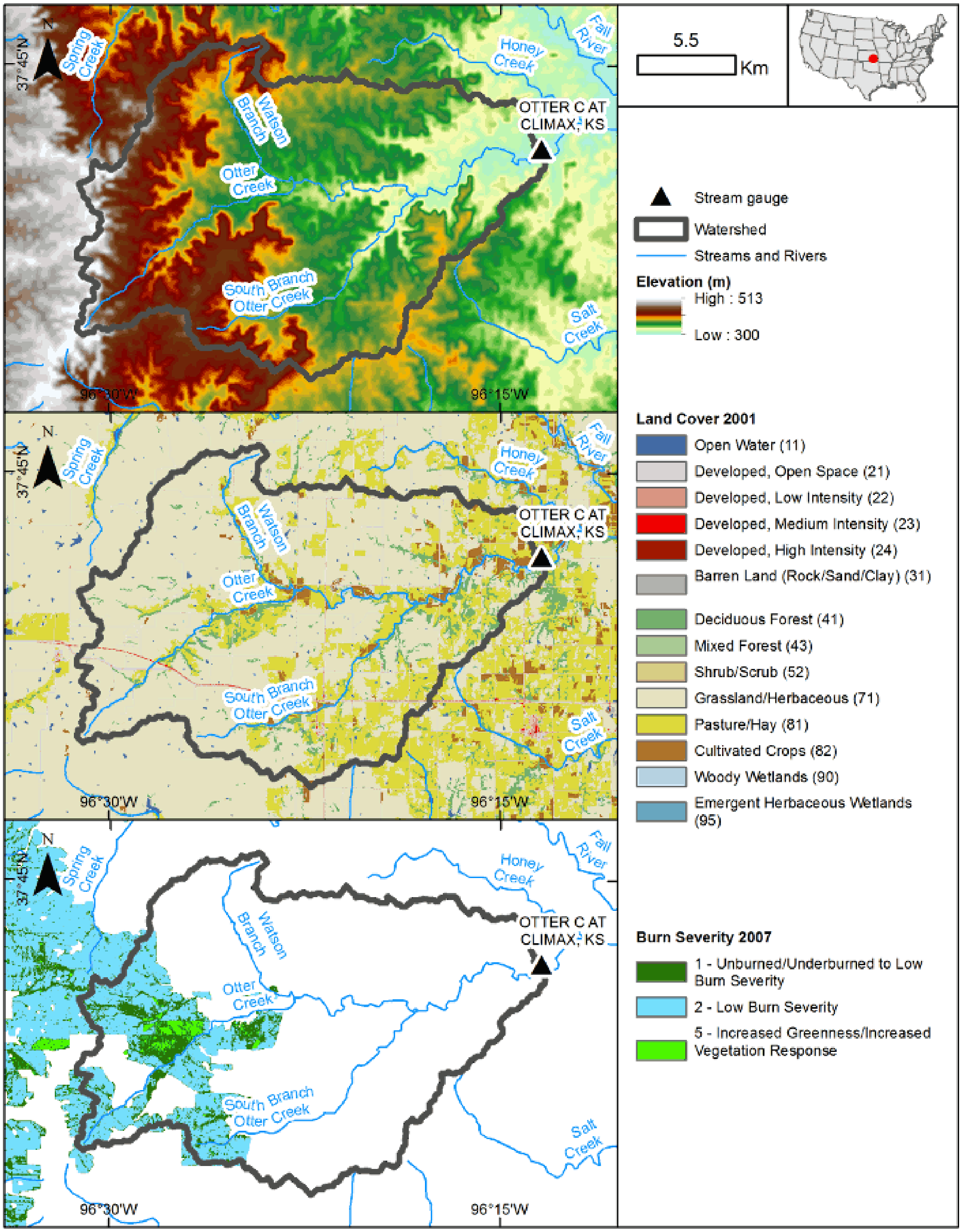
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	827	822	-5	-0.6

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM4	826.8	822.2	-4.6	-0.6

Otter Creek at Climax, Kansas (Gauge 7167500)/2007 Unnamed Fire



Otter Creek near Climax, Kansas

Water Resource Region: Arkansas-White-Red (HUC-2 code 11) Climate Type (Köppen): Dfa

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
7167500	37.70821 N	96.223602 E	319.6	1.91

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
309	507	382	13.2	2.6

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
6%	0%	0%	65%	24%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
0%	1%	1%	3%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Unnamed	4/1/2007	Unknown	67.2	21.0%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
5.7%	15.3%	0.0%	0.0%	0.8%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	991	1144	153	15.5

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	741	1118	377	50.9

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	4666	6247	1581	33.9

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	865	848	-17	-2.0

River Flow (5 Years Before and After Wildland Fire)

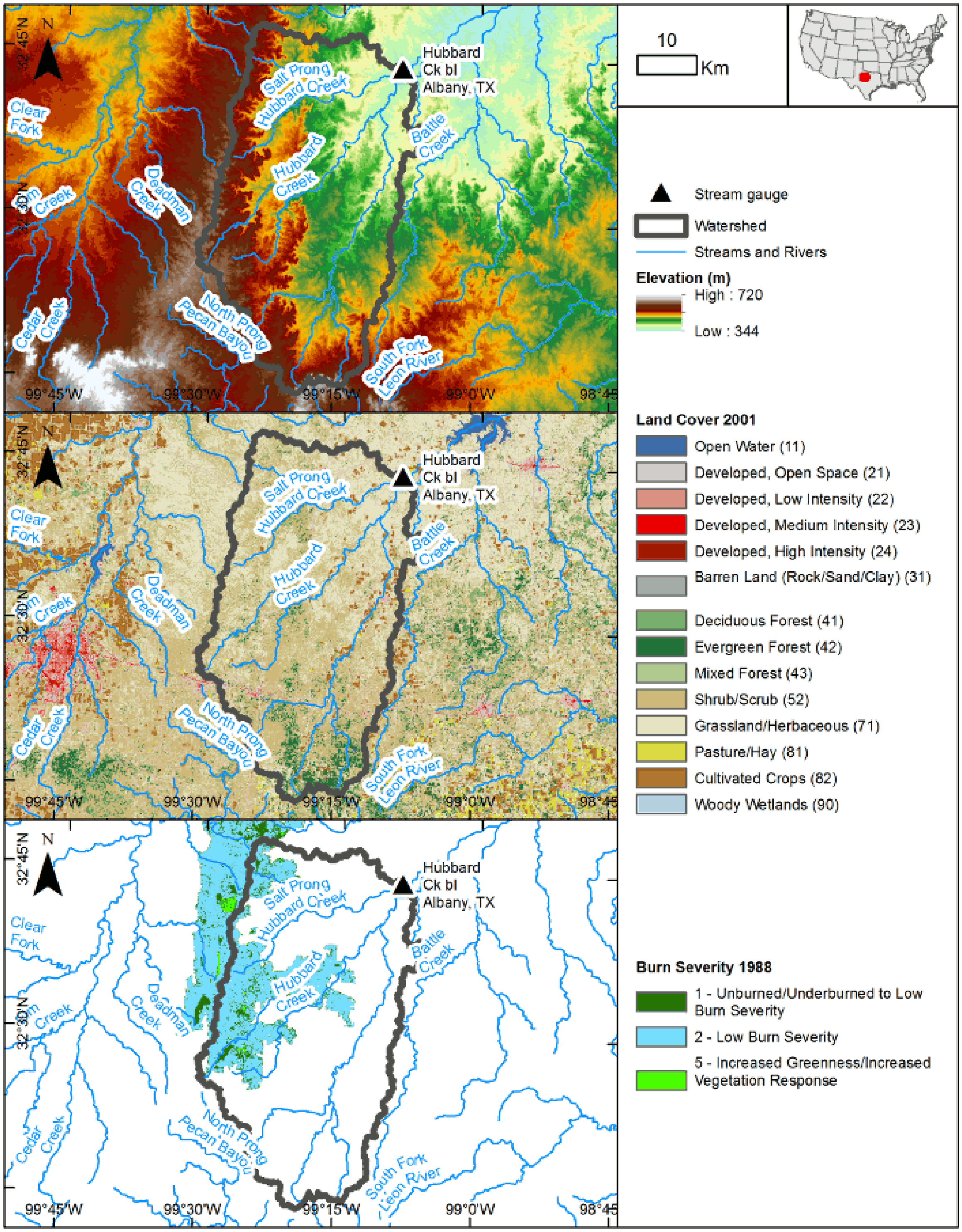
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	295	367	72	24.4

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM2	105.0	-33.1	35.6	-11.2

Hubbard Creek near Albany, Texas (Gauge 8086212)/1988 Big Country Wildfire



Hubbard Creek near Albany, Texas

Water Resource Region: Texas-Gulf (HUC-2 code 12) Climate Type (Köppen): Cfa

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
8086212	32.732897 N	99.14063 E	1584.8	2.09

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
369	669	485	20.8	2.5

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
3%	5%	0%	35%	3%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
49%	0%	0%	5%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Big Country	3/12/1988	Wildfire	368.4	23.2%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
3.5%	19.7%	0.0%	0.0%	0.2%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	656	779	123	18.7

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	9	30	21	219.9

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	2105	2389	284	13.5

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	1052	1040	-13	-1.2

River Flow (5 Years Before and After Wildland Fire)

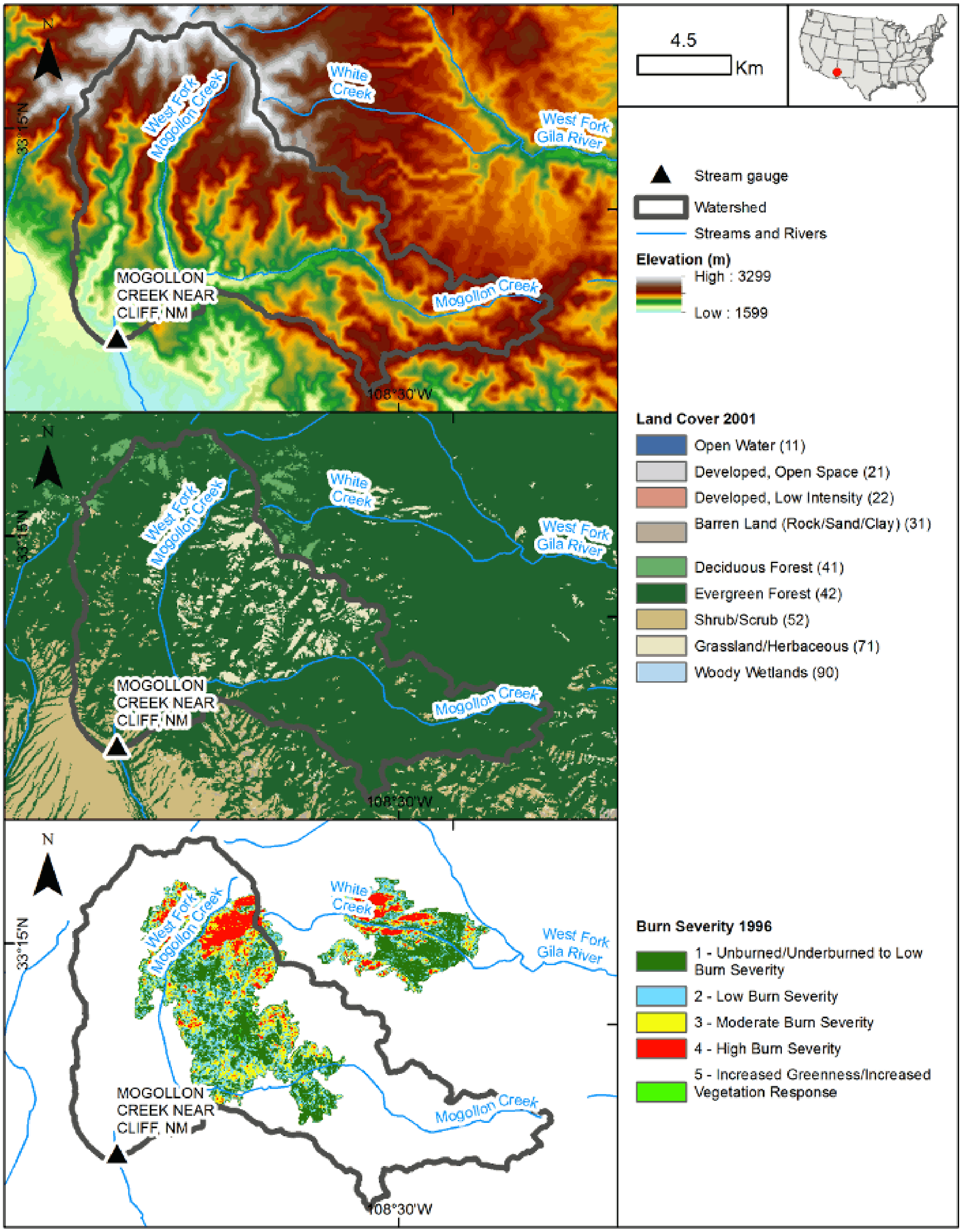
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	21	54	33	158.7

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM3	12.8	20.4	61.1	97.6

Mogollon Creek near Cliff, New Mexico (Gauge 9430600)/1996 Lookout Wildfire



Mogollon Creek near Cliff, New Mexico

Water Resource Region: Lower Colorado (HUC-2 code 15) Climate Type (Köppen): Csb

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
9430600	33.166733 N	108.649779 E	190.5	1.64

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
1675	3261	2388	80.5	28.6

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
1%	85%	0%	9%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
4%	0%	0%	0%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Lookout	6/8/1996	Wildfire	60.7	32.1%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
13.6%	9.5%	5.8%	3.2%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	658	562	-95	-14.5

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	3609	2429	-1179	-32.7

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	2340	2755	415	17.8

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	664	692	28	4.2

River Flow (5 Years Before and After Wildland Fire)

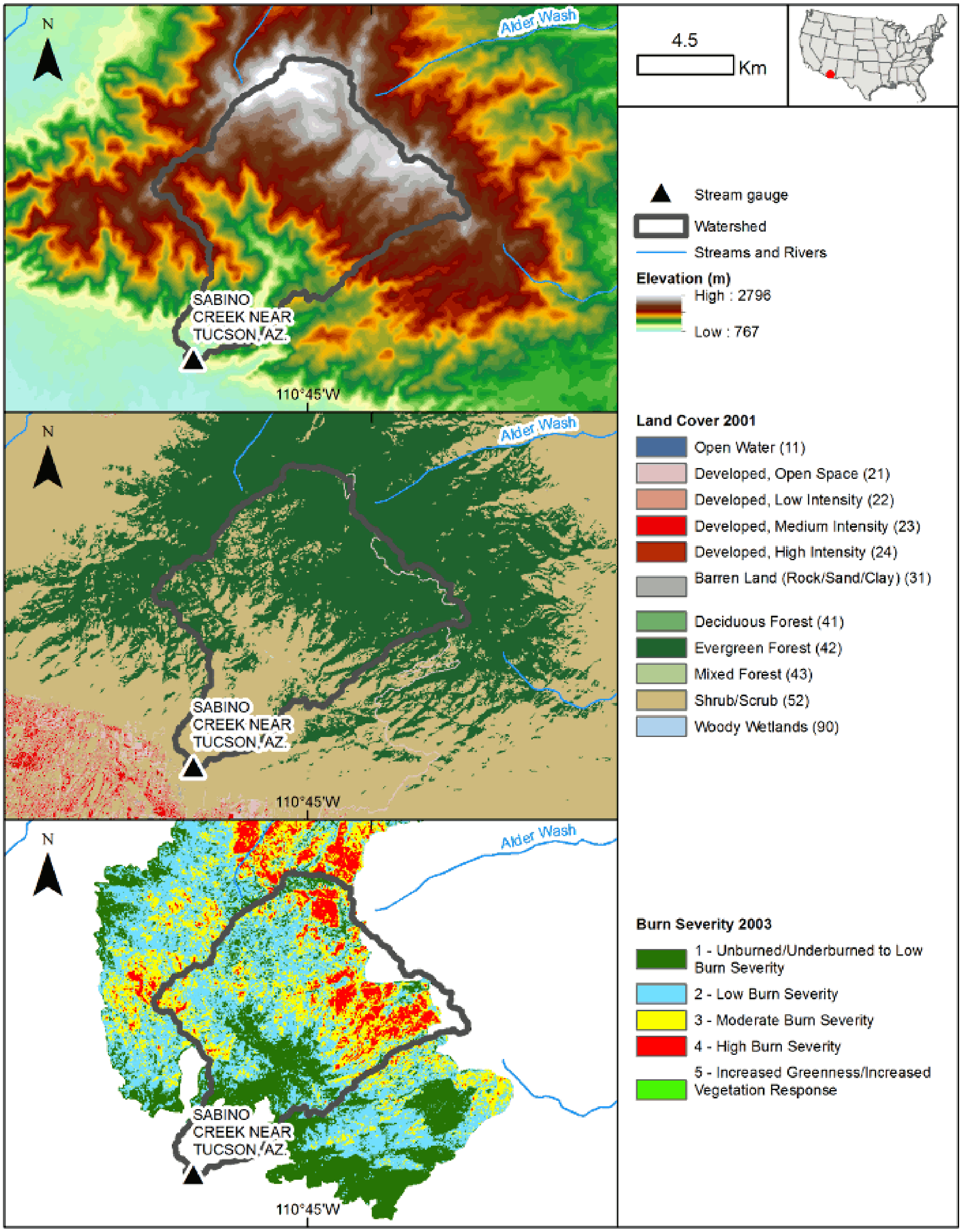
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	245	105	-140	-57.2

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM3	4.7	-144.6	1.9	-59.1

Sabino Creek near Tucson, Arizona (Gauge 9484000)/2003 Unnamed Wildfire



Sabino Creek near Tucson, Arizona

Water Resource Region: Lower Colorado (HUC-2 code 15) Climate Type (Köppen): BSh

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
9484000	32.316742 N	110.810367 E	103.7	1.83

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
854	2781	1902	73.4	26.5

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	62%	0%	0%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
37%	0%	0%	1%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Unnamed	6/17/2003	Wildfire	90.5	87.2%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
20.3%	37.0%	21.5%	8.4%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	604	479	-125	-20.7

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	448	110	-337	-75.3

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	3391	1945	-1446	-42.6

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	1023	1034	11	1.1

River Flow (5 Years Before and After Wildland Fire)

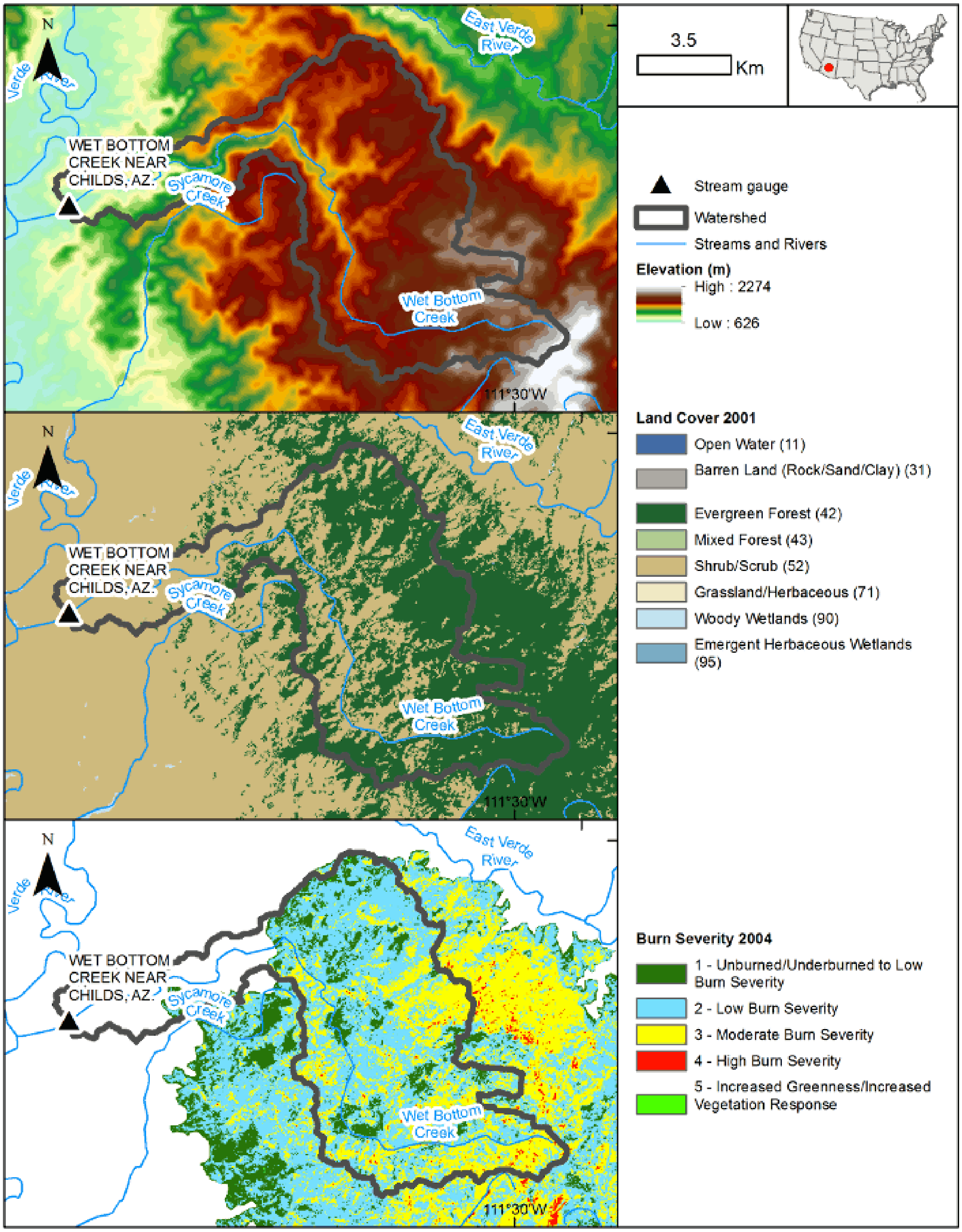
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	104	151	47	45.0

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM4	-86.9	133.6	-83.6	128.6

Wet Bottom Creek near Childs, Arizona (Gauge 9508300)/2004 Willow Wildfire



Wet Bottom Creek near Childs, Arizona

Water Resource Region: Lower Colorado (HUC-2 code 15) — Climate Type (Köppen): BSh

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
9508300	34.160868 N	111.692924 E	93.0	2.57

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
734	2204	1493	69.4	18.6

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	57%	0%	0%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
43%	0%	0%	0%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Willow	6/24/2004	Wildfire	79.1	84.2%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
10.8%	49.2%	24.2%	0.0%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	465	581	115	24.8

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	27	12	-15	-54.0

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	2613	3045	432	16.5

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	904	863	-41	-4.5

River Flow (5 Years Before and After Wildland Fire)

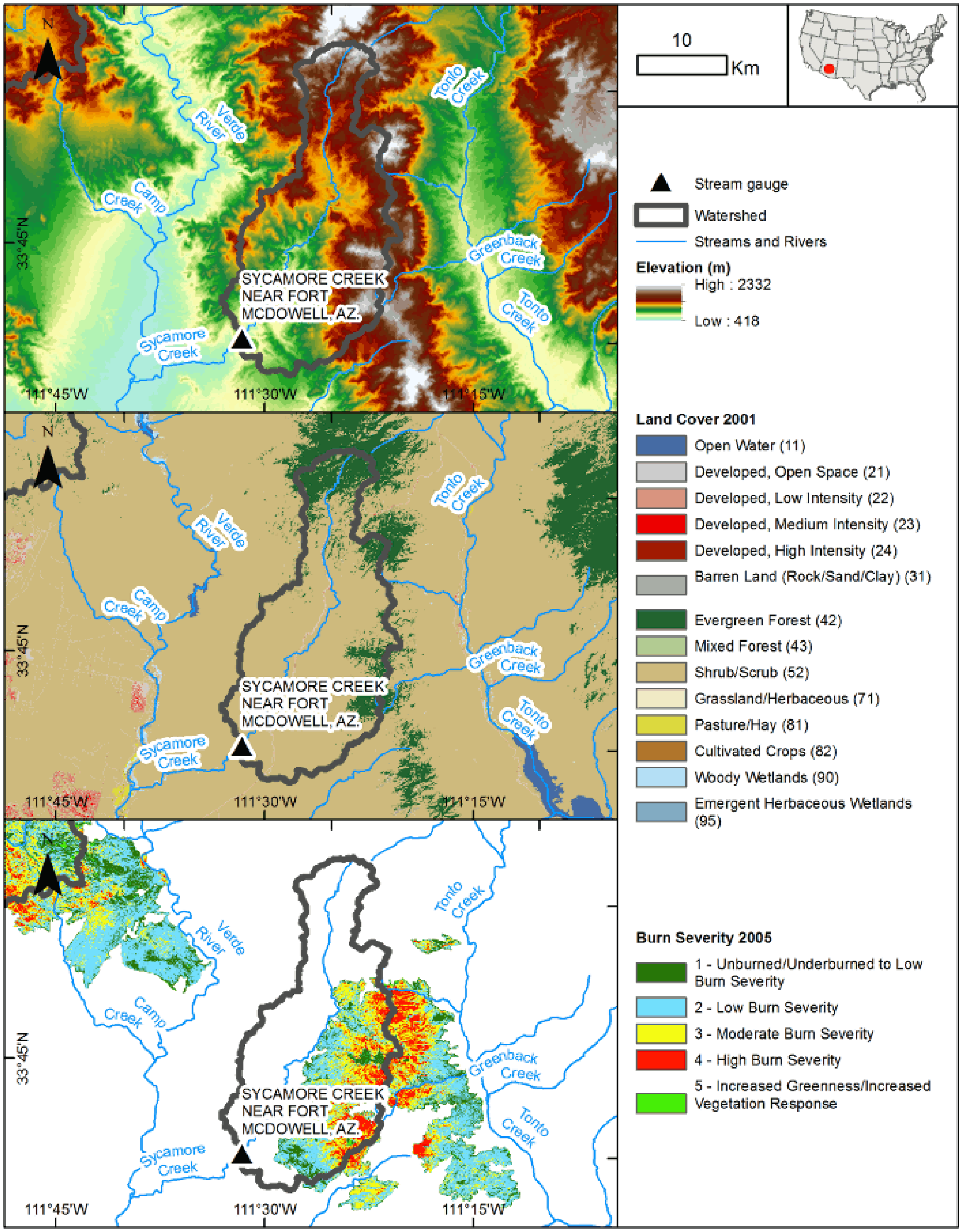
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	50	184	134	266.9

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM3	36.9	97.0	73.5	193.4

Sycamore Creek near Fort McDowell, Arizona (Gauge 9510200)/2005 Edge Complex Wildfires



Sycamore Creek near Fort McDowell, Arizona

Water Resource Region: Lower Colorado (HUC-2 code 15) Climate Type (Köppen): BSh

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km²)*	*Shape Parameter*
9510200	33.694211 N	111.541802 E	425.3	2.14

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
547	2075	1166	60.0	15.7

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	15%	0%	0%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
84%	0%	0%	1%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km²)*	*Burned Area to Drainage Area Ratio (%)*
Edge Complex	7/16/2005	Wildfire	168.0	39.5%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
5.7%	15.8%	13.4%	4.6%	0.1%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	355	355	0	0.0

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	6	20	14	212.8

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1349	1600	251	18.6

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	1115	1066	-49	-4.4

River Flow (5 Years Before and After Wildland Fire)

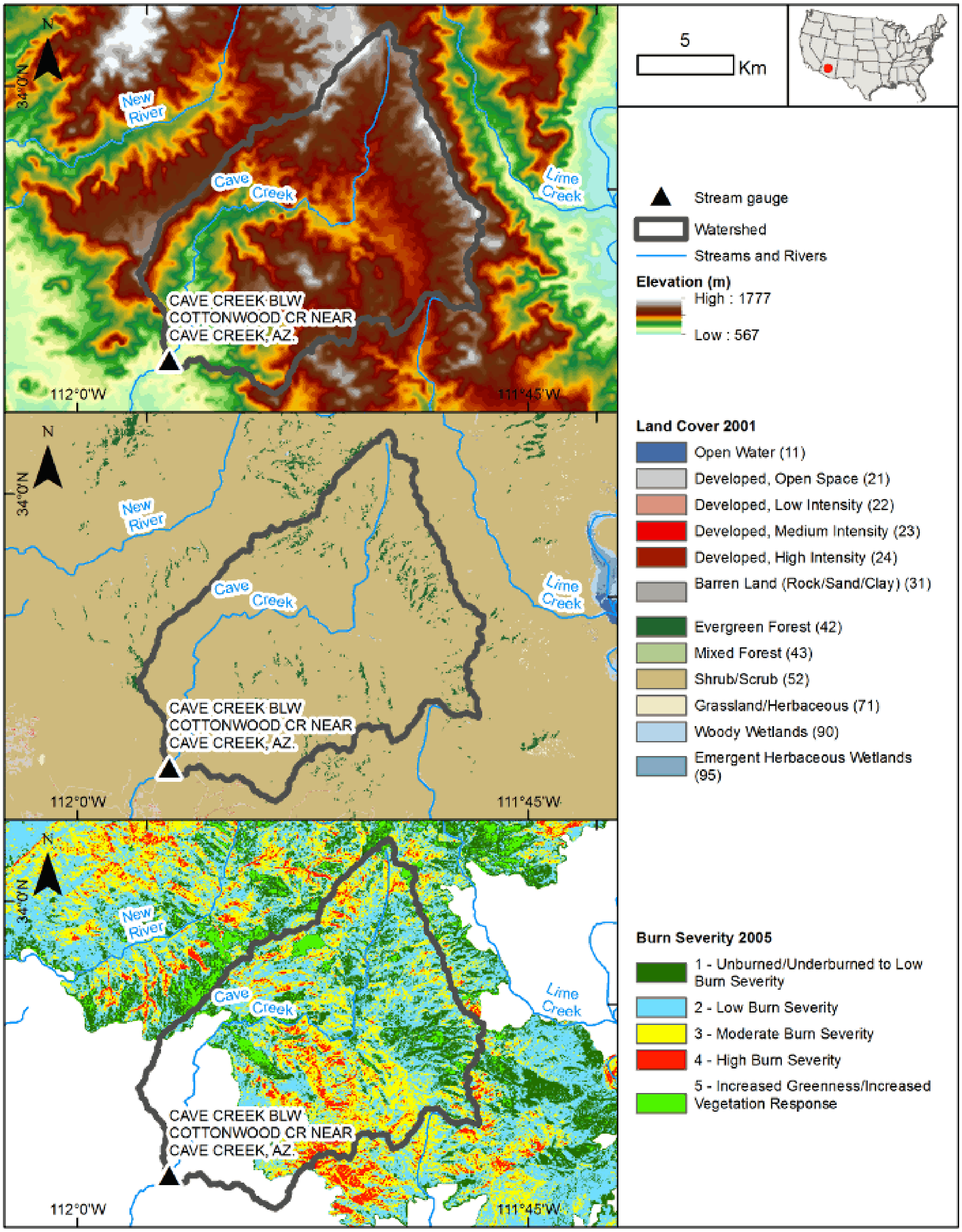
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	12	69	57	463.5

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM2	-6.3	63.3	-51.0	514.5

Cave Creek near Cave Creek, Arizona (Gauge 9512280)/2005 Cave Creek Complex Wildfire



Cave Creek near Cave Creek, Arizona

Water Resource Region: Lower Colorado (HUC-2 code 15) Climate Type (Köppen): BSh

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
9512280	33.88726 N	111.954039 E	188.7	1.81

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
698	1628	1148	56.2	14.8

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	3%	0%	0%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
97%	0%	0%	0%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Cave Creek Complex	6/21/2005	Wildfire	142.4	75.5%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
14.9%	33.9%	24.0%	2.7%	2.7%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	376	378	2	0.6

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	0	0	0	-100.0

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1744	1878	133	7.6

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	1155	1107	-47	-4.1

River Flow (5 Years Before and After Wildland Fire)

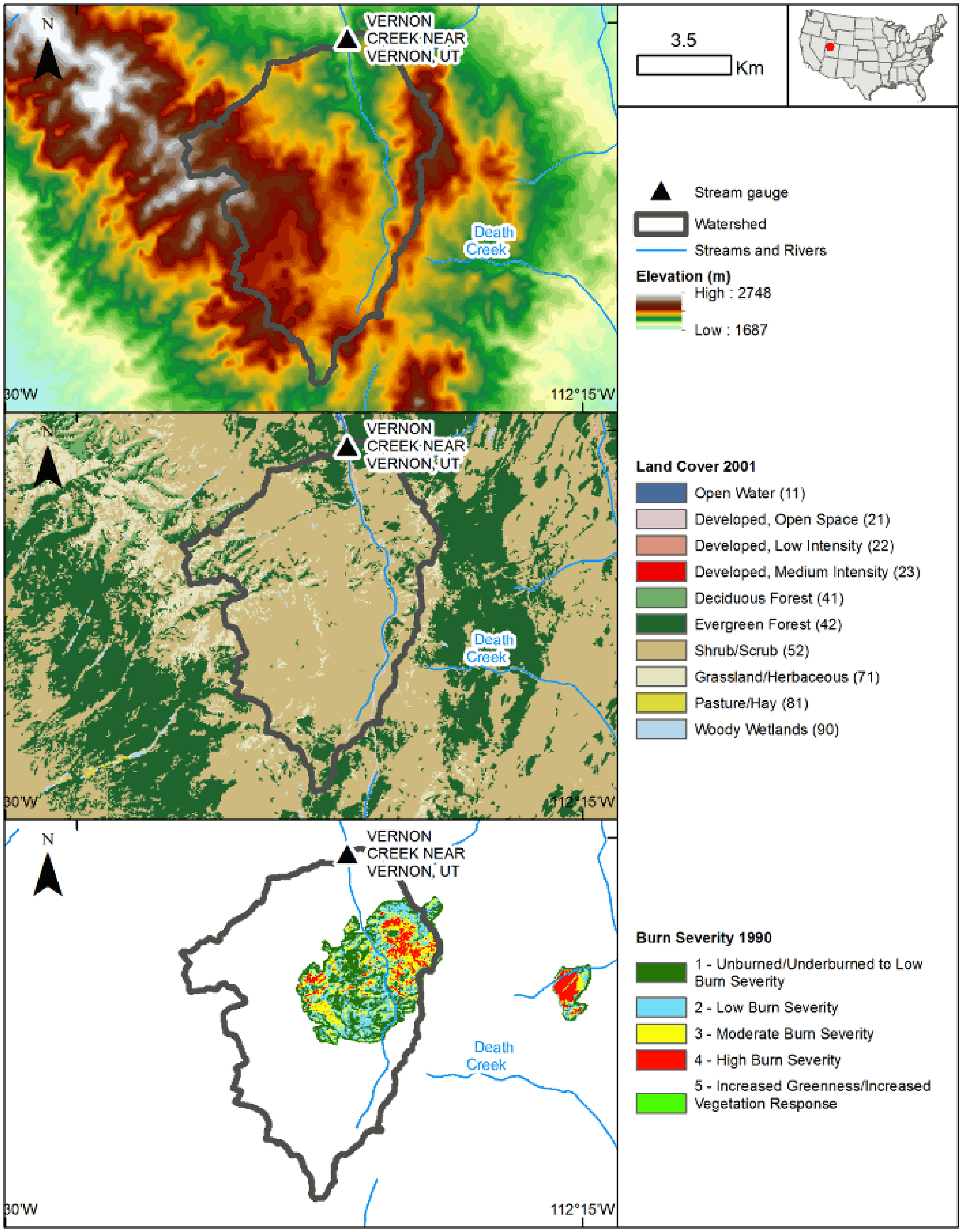
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	6	41	35	616.8

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM3	0.2	35.0	2.8	613.9

Vernon Creek near Vernon, Utah (Gauge 10172700)/1990 Cherry Wildfire



Vernon Creek near Vernon, Utah

Water Resource Region: Great Basin (HUC-2 code 16) — Climate Type (Köppen): BSk

Gage Number	Latitude	Longitude	Drainage Area (km^2)	Shape Parameter
10172700	39.979391 N	112.38023 E	69.9	1.79

Topography (GMTED2010)

Lowest Elevation (m)	Highest Elevation (m)	Mean Elevation (m)	Maximum Slope (%)	Mean Slope (%)
1902	2500	2155	33.0	10.7

Land Cover (NLCD 2001)

Deciduous Forest	Evergreen Forest	Mixed Forest	Grassland-Herbaceous	Cultivated Crop
0%	12%	0%	7%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
80%	1%	0%	1%	0%

Wildland Fire (MTBS)

Name	Date	Type	Burned Area (km^2)	Burned Area to Drainage Area Ratio (%)
Cherry	7/29/1990	Wildfire	19.4	27.6%

Unburned-Underburned	Low Severity	Moderate Severity	High Severity	Increased Greenness
11.9%	7.5%	6.3%	1.9%	0.1%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
Daymet	480	530	50	10.5

Annual Snow Water Equivalent

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
Daymet	5176	13690	8514	164.5

Monthly Precipitation Variance

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
Daymet	819	985	166	20.3

Annual Potential Evapotranspiration

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
PRISM	643	589	-54	-8.3

River Flow (5 Years Before and After Wildland Fire)

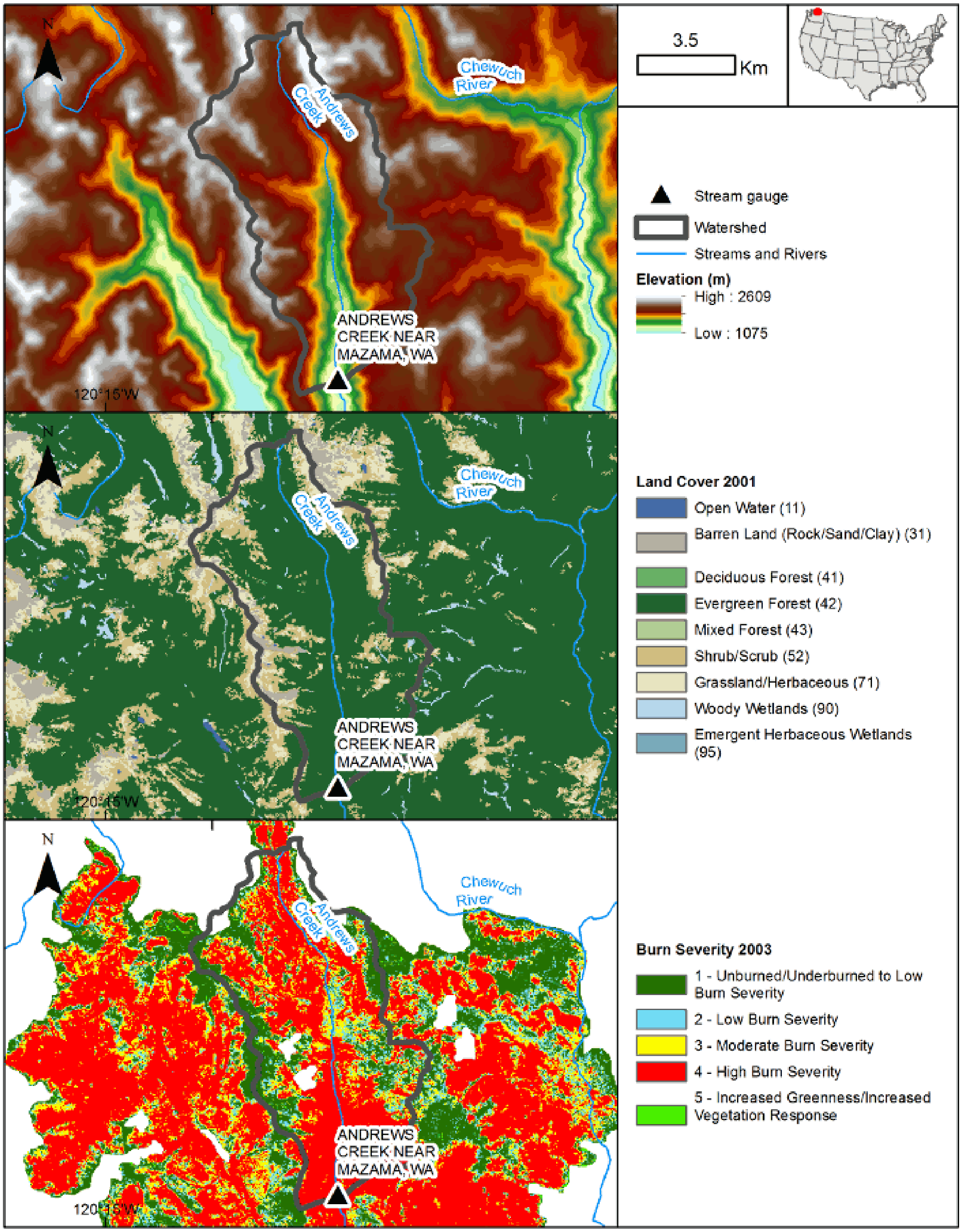
Annual River Flow

Source	Pre-fire (mm)	Post-fire (mm)	Change (mm)	Change (%)
GAGES-II	73	27	-45	-62.7

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	Change Attributed to Climate (mm)	Change Attributed to Wildland Fire (mm)	Change Attributed to Climate (%)	Change Attributed to Wildland Fire (%)
CEM1	13.3	-58.7	18.3	-81.0

Andrews Creek near Mazama, Washington (Gauge 12447390)/2003 Fawn Peak Complex (Farewell Wildfire)



Andrews Creek near Mazama, Washington

Water Resource Region: Pacific Northwest (HUC-2 code 17) Climate Type (Köppen): Dfb

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
12447390	48.822925 N	120.145924 E	58.1	1.41

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
1348	2528	1943	84.2	28.7

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	74%	0%	8%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
15%	0%	0%	0%	4%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Fawn Peak Complex (Farewell)	6/30/2003	Wildfire	55.6	95.6%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
22.5%	5.2%	13.3%	54.6%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	867	838	-28	-3.3

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	72618	46353	-26265	-36.2

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	4638	3829	-810	-17.5

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	412	442	30	7.2

River Flow (5 Years Before and After Wildland Fire)

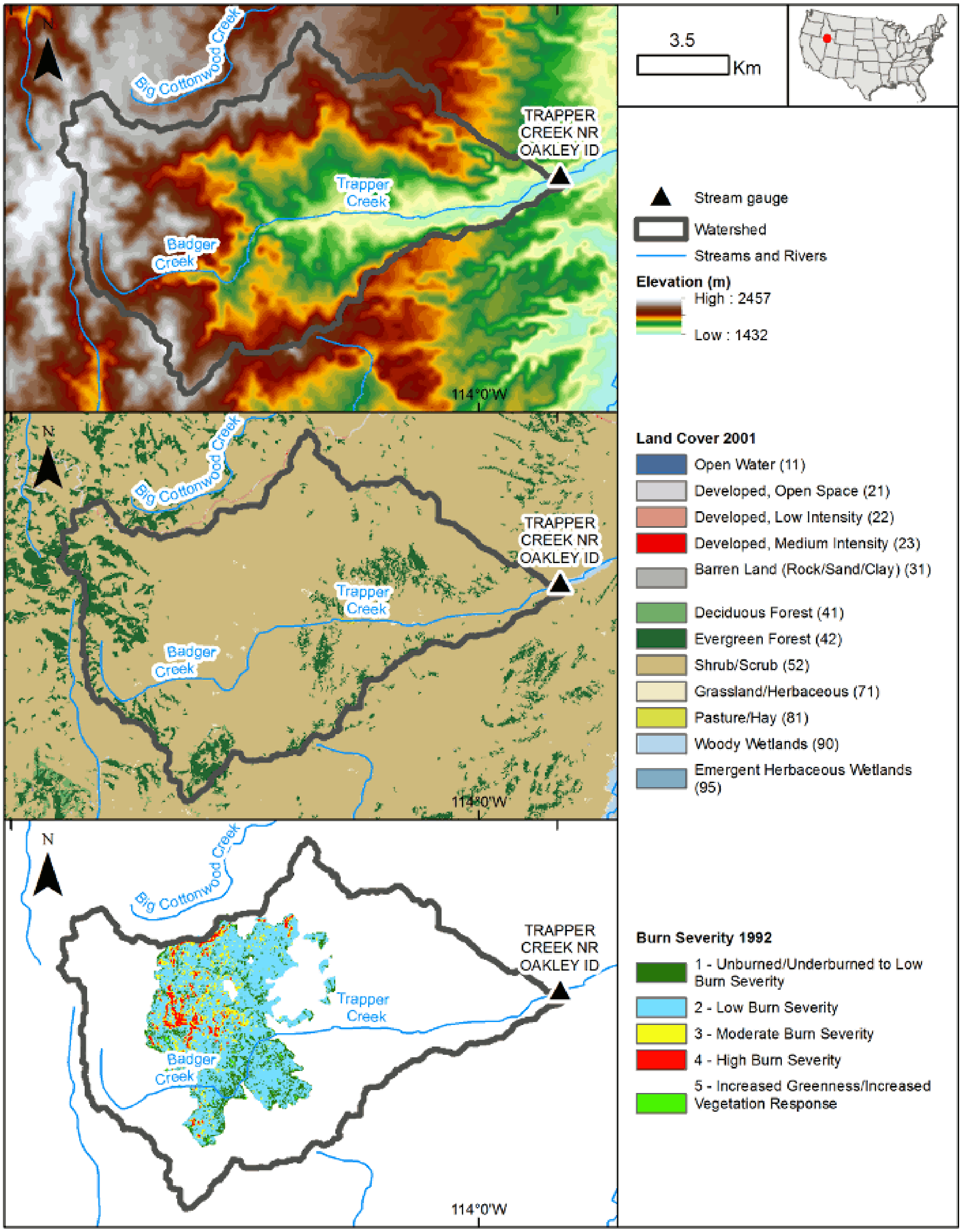
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	457	531	74	16.1

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM4	-147.0	220.6	-32.1	48.2

Trapper Creek near Oakley, Idaho (Gauge 13083000)/1992 Trapper Wildfire



Trapper Creek near Oakley, Idaho

Water Resource Region: Pacific Northwest (HUC-2 code 17) Climate Type (Köppen): BSk

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
13083000	42.165833 N	113.983611 E	133.2	1.89

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
1485	2394	1940	52.3	16.6

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	10%	0%	0%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
89%	0%	0%	0%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Trapper	8/21/1992	Wildfire	36.5	27.4%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
3.5%	22.0%	0.9%	1.0%	0.1%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	451	603	152	33.7

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	8155	11517	3363	41.2

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1025	1802	777	75.8

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	607	592	-15	-2.5

River Flow (5 Years Before and After Wildland Fire)

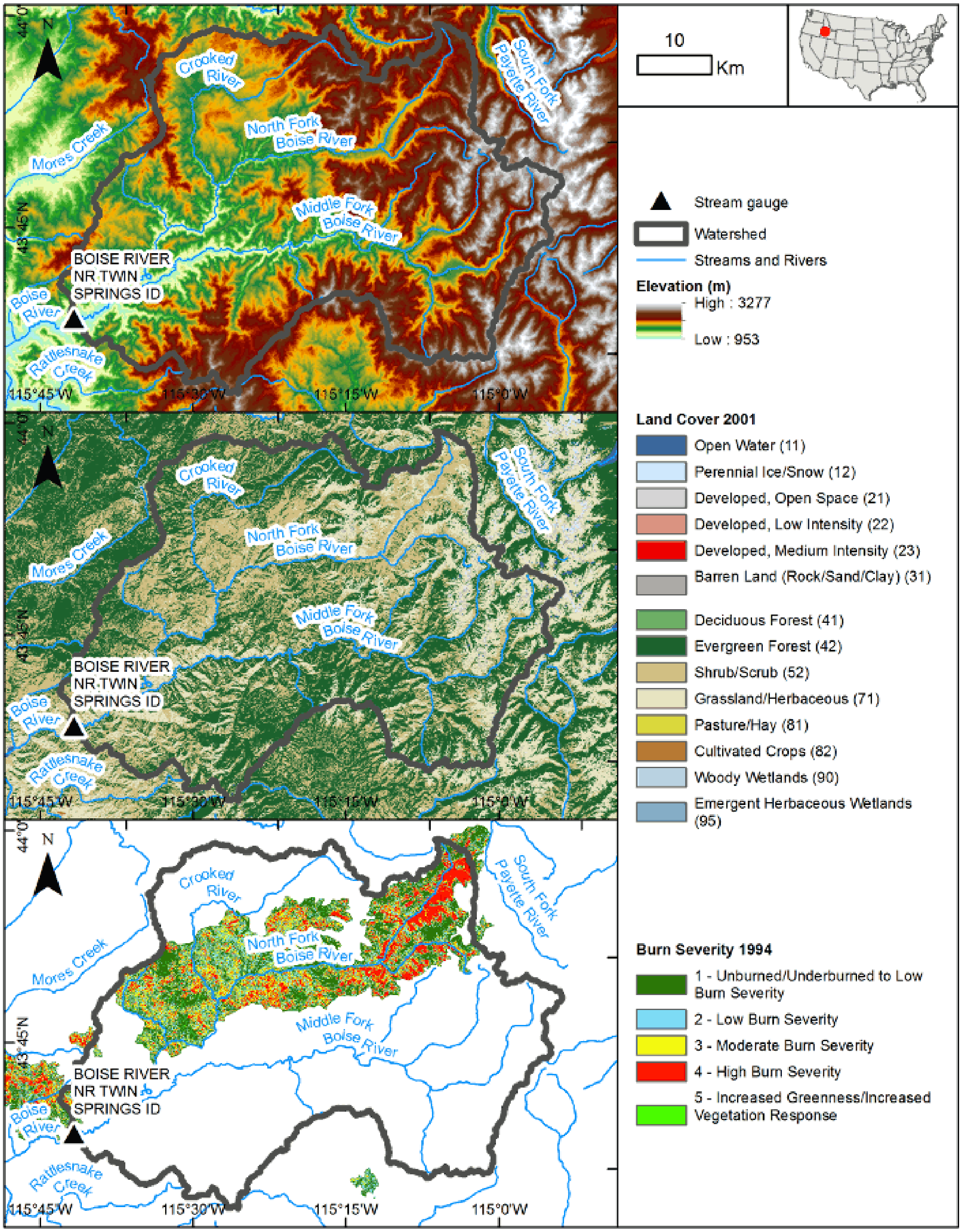
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	78	88	10	12.9

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM3	-8.1	18.2	-10.3	23.2

Boise River near Twin Springs, Idaho (Gauge 13185000)/1994 Idaho City Complex (Rabbit Creek Wildfire)



Boise River near Twin Springs, Idaho

Water Resource Region: Pacific Northwest (HUC-2 code 17) Climate Type (Köppen): Dsa

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
13185000	43.659444 N	115.727222 E	2154.4	2.06

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
1007	3113	1956	88.4	26.8

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	45%	0%	20%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
34%	0%	0%	0%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Idaho City Complex (Rabbit Creek)	7/28/1994	Wildfire	610.1	28.3%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
11.8%	5.9%	6.0%	4.6%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	795	1097	303	38.1

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	42857	60267	17411	40.6

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	2983	6956	3974	133.2

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	486	497	11	2.3

River Flow (5 Years Before and After Wildland Fire)

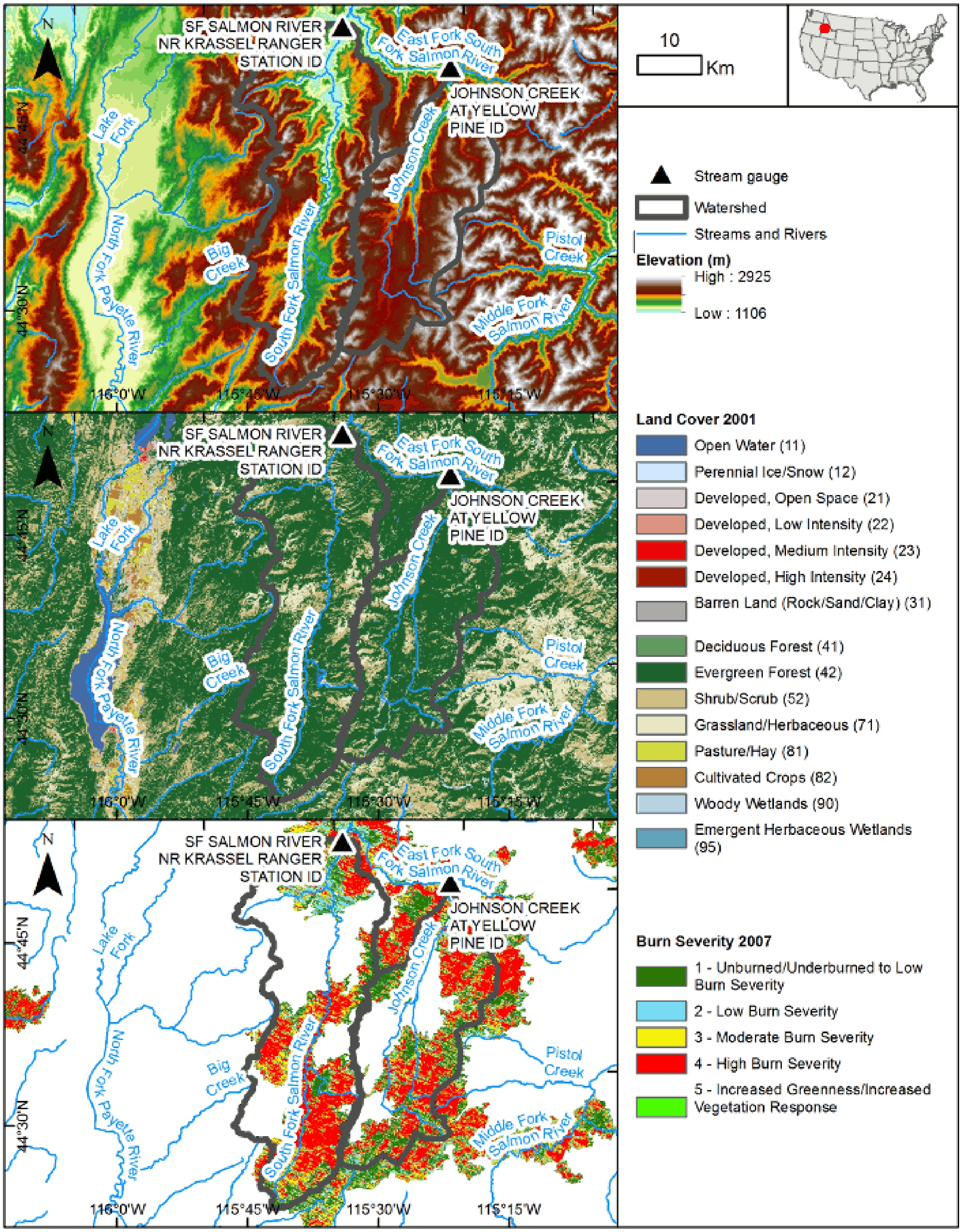
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	363	615	252	69.3

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM2	-227.1	478.9	-62.5	131.9

South Fork Salmon River near Krassel Ranger Station, Idaho (Gauge 13310700)/2007 Cascade Complex (Monumental Wildfire)



South Fork Salmon River near Krassel Ranger Station, Idaho

Water Resource Region: Pacific Northwest (HUC-2 code 17) Climate Type (Köppen): Dsb

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
13310700	44.986944 N	115.725000 E	853.1	2.25

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
1165	2740	1946	76.4	25.0

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	75%	0%	7%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
16%	0%	0%	0%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Cascade Complex (Monumental)	7/17/2007	Wildfire	346.6	40.6%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
8.6%	6.9%	8.7%	16.4%	0.1%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1110	1018	-91	-8.2

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	37677	44708	7031	18.7

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	6598	4115	-2483	-37.6

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	477	465	-12	-2.6

River Flow (5 Years Before and After Wildland Fire)

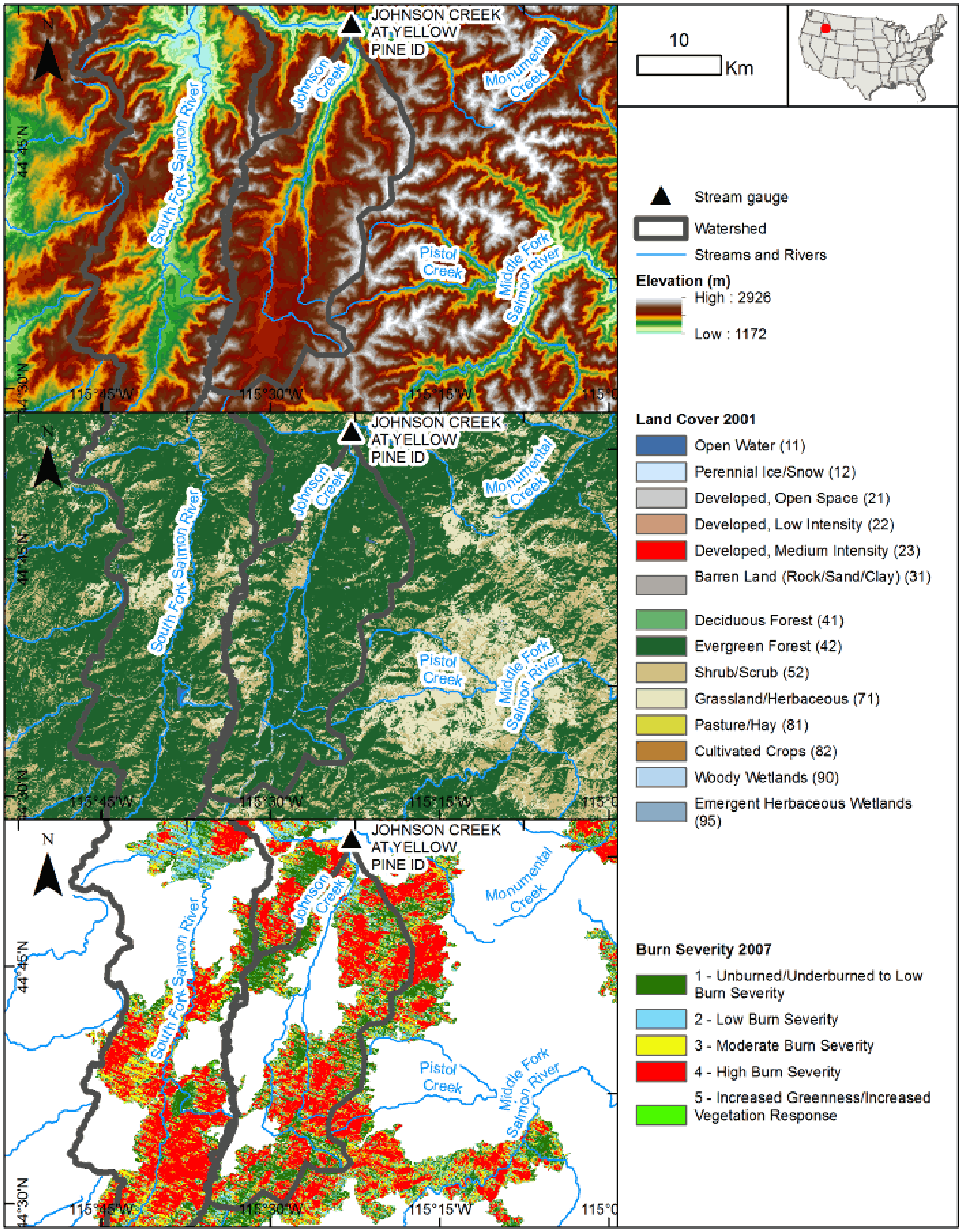
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	500	575	75	15.0

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM4	-6.8	81.8	-1.4	16.4

Johnson Creek at Yellow Pine, Idaho (Gauge 13313000)/2007 Cascade Complex (Monumental Wildfire)



Johnson Creek at Yellow Pine, Idaho

Water Resource Region: Pacific Northwest (HUC-2 code 17) Climate Type (Köppen): Dsb

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
13313000	44.961667 N	115.500000 E	561.9	1.46

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
1423	2749	2183	77.7	20.6

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	79%	0%	6%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
13%	1%	0%	0%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Cascade Complex (Monumental)	7/17/2007	Wildfire	310.0	55.3%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
18.5%	8.0%	8.8%	20.0%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1345	1253	-92	-6.9

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	68935	72983	4048	5.9

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	10453	6620	-3834	-36.7

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	452	438	-14	-3.1

River Flow (5 Years Before and After Wildland Fire)

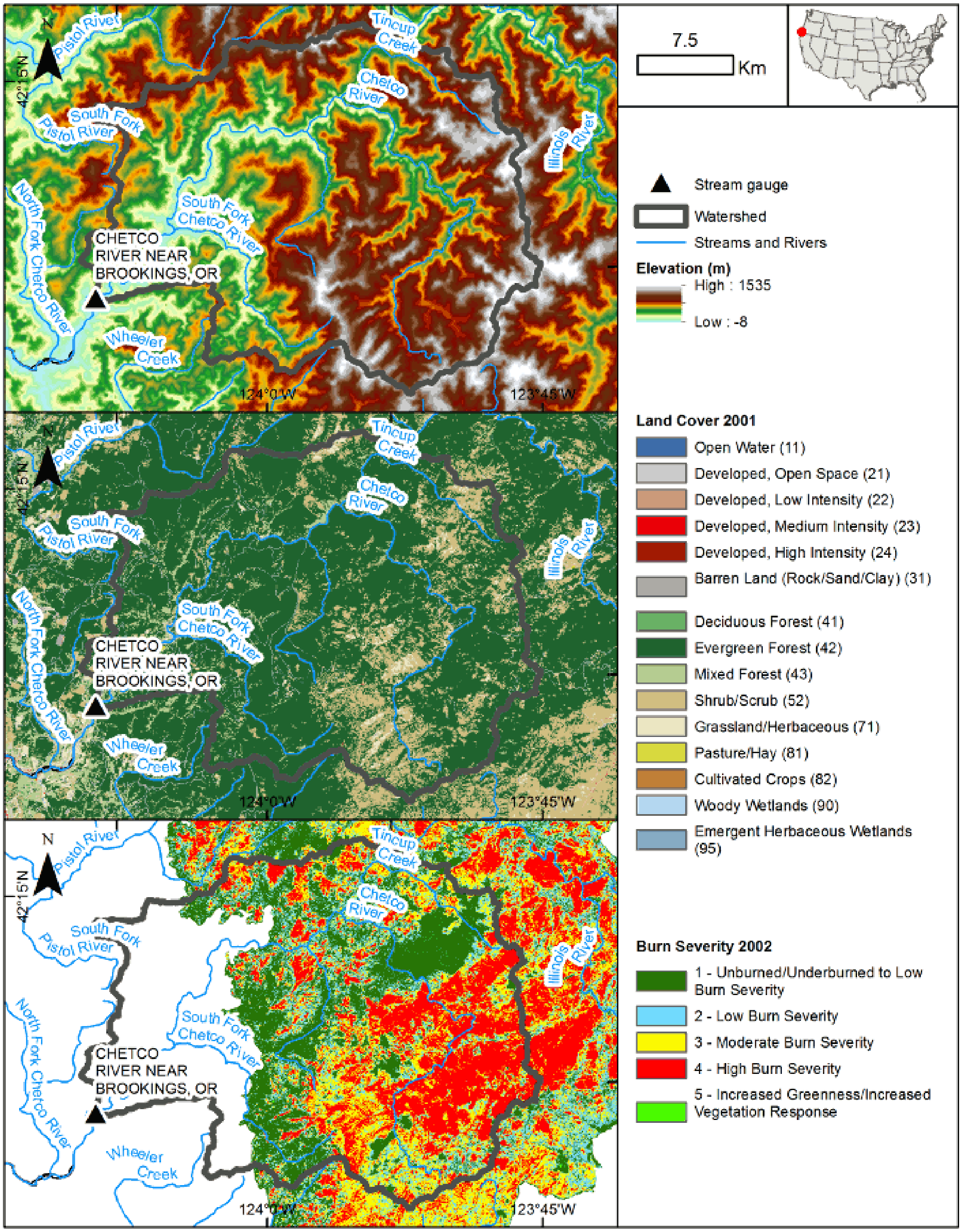
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	487	588	101	20.8

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM4	-16.8	117.9	-3.5	24.2

Chetco River near Brookings, Oregon (Gauge 14400000)/2002 Biscuit Complex (Biscuit Wildfire)



Chetco River near Brookings, Oregon

Water Resource Region: Pacific Northwest (HUC-2 code 17) | Climate Type (Köppen): Csb

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
14400000	42.123443 N	124.187311 E	702.6	1.83

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
37	1531	675	79.2	27.3

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	76%	5%	2%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
15%	0%	0%	2%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Biscuit Complex (Biscuit)	7/13/2002	Wildfire	527.4	75.1%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
25.3%	11.8%	16.0%	22.0%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	2051	2087	36	1.8

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	2	12	9	403.4

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	28527	35757	7230	25.3

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	691	709	18	2.7

River Flow (5 Years Before and After Wildland Fire)

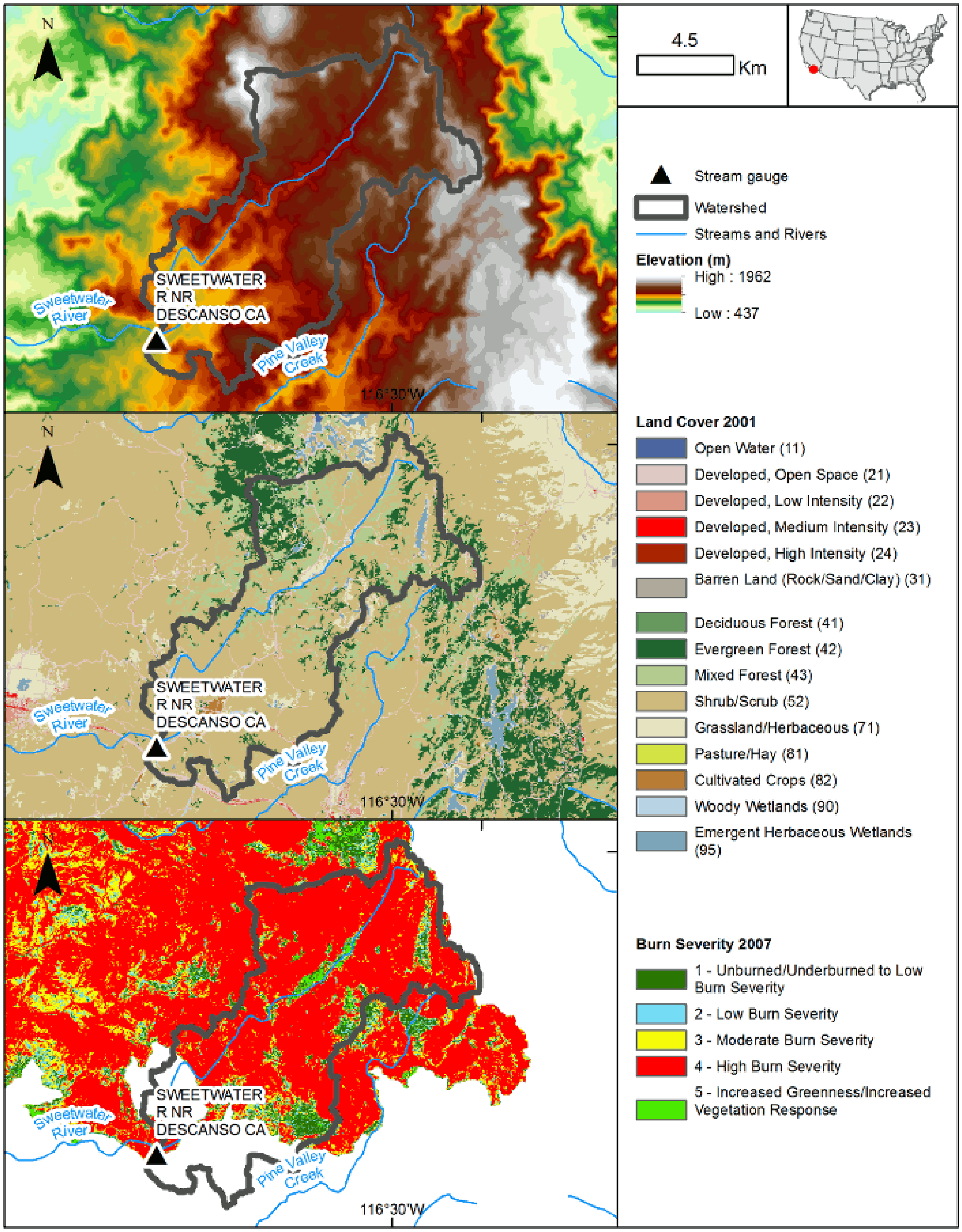
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	2695	3044	349	13.0

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM3	7.6	341.7	0.3	12.7

Sweetwater River near Descanso, California (Gauge 11015000)/2003 Cedar Wildfire



Sweetwater River near Descanso, California

Water Resource Region: California (HUC-2 code 18) Climate Type (Köppen): Csb

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km²)*	*Shape Parameter*
11015000	32.834774 N	116.623075 E	117.8	2.35

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
1009	1891	1334	40.3	13.0

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	11%	14%	4%	1%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
63%	2%	0%	5%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km²)*	*Burned Area to Drainage Area Ratio (%)*
Cedar	10/25/2003	Wildfire	96.6	81.9%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
7.3%	1.7%	5.8%	67.2%	0.7%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	574	566	-8	-1.4

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	32	2	-31	-94.9

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	4605	4330	-275	-6.0

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	751	790	39	5.2

River Flow (5 Years Before and After Wildland Fire)

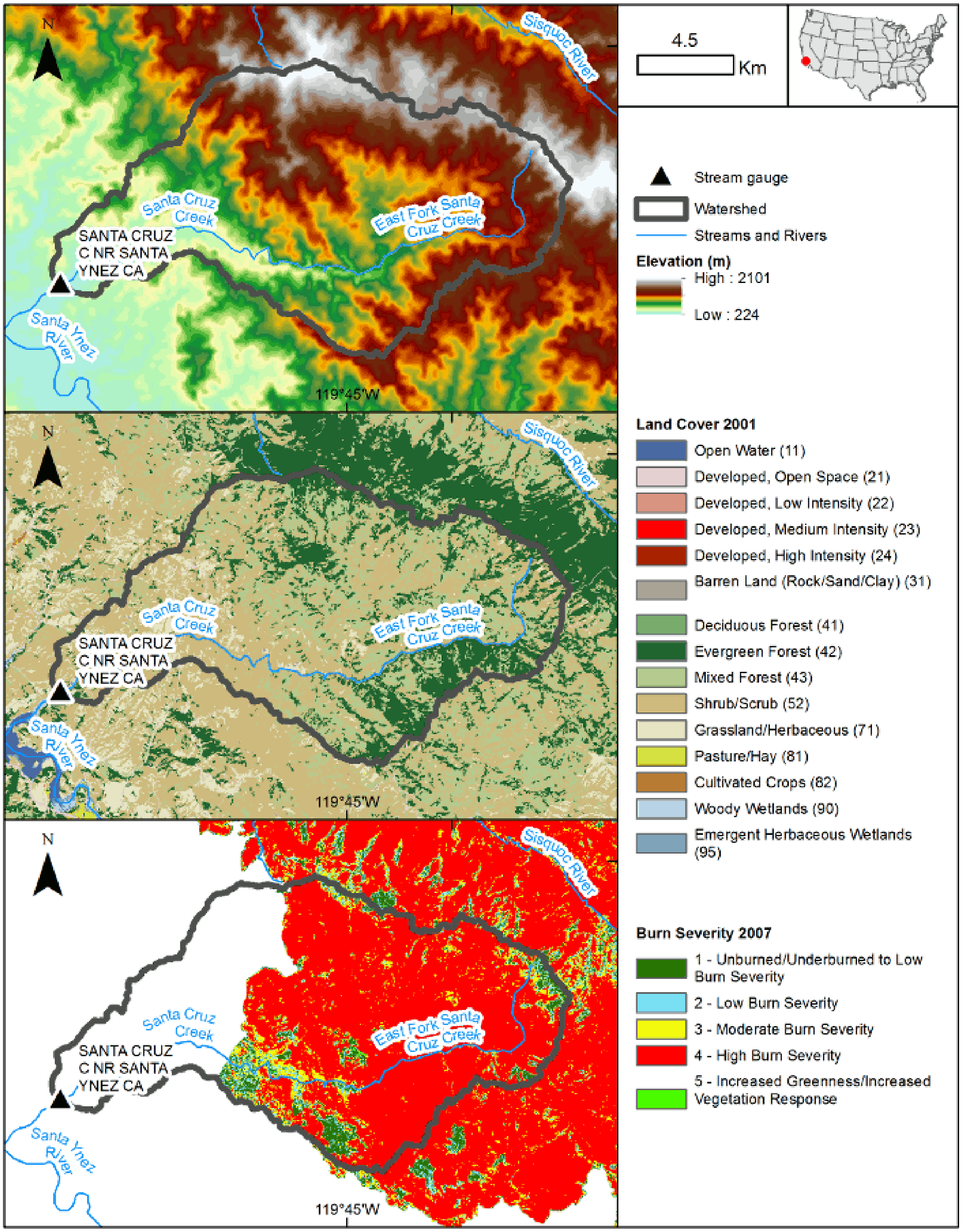
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	51	43	-8	-15.5

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM2	-32.3	24.3	-62.8	47.4

Santa Cruz Creek near Santa Ynez, California (Gauge 11124500)/2007 Zaca Wildfire



Santa Cruz Creek near Santa Ynez, California

Water Resource Region: California (HUC-2 code 18) — Climate Type (Köppen): Csb

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
11124500	34.596656 N	119.908752 E	191.5	1.85

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
253	1990	1038	69.7	24.8

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	22%	24%	7%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
47%	0%	0%	1%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Zaca	7/4/2007	Wildfire	137.6	71.5%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
4.6%	2.6%	5.0%	59.3%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	705	618	-87	-12.3

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	15	21	6	44.2

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	8408	8209	-200	-2.4

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	762	810	48	6.4

River Flow (5 Years Before and After Wildland Fire)

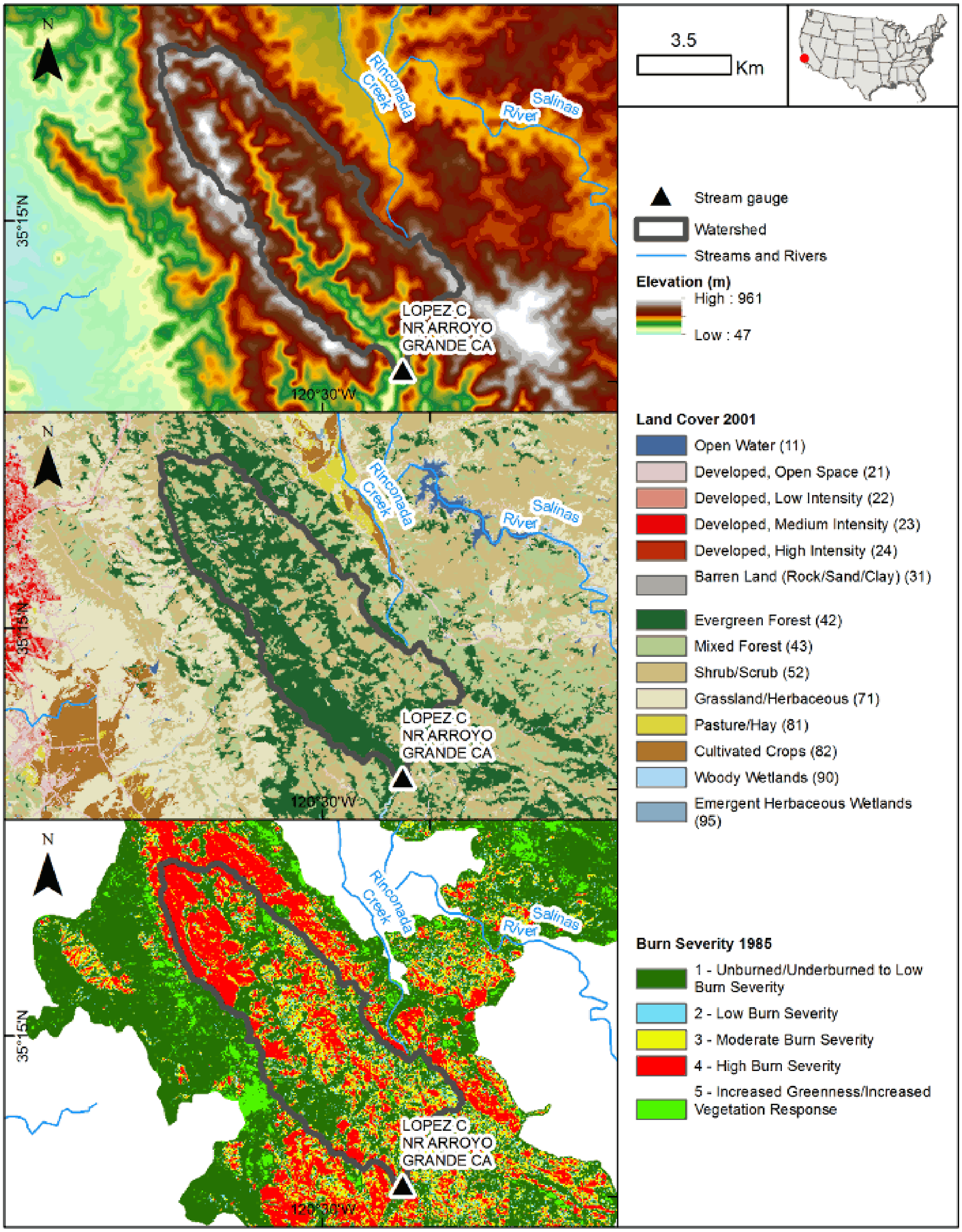
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	96	96	0	-0.5

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM2	-147.1	146.6	-153.2	152.7

Lopez Creek near Arroyo Grande, California (Gauge 11141280)/1985 Las Pilitas Wildfire



Lopez Creek near Arroyo Grande, California

Water Resource Region: California (HUC-2 code 18) Climate Type (Köppen): Csb

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
11141280	35.23553 N	120.472386 E	54.0	2.00

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
213	865	557	61.1	22.4

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	56%	14%	1%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
27%	0%	0%	1%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Las Pilitas	7/1/1985	Wildfire	53.8	99.5%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
45.3%	1.7%	18.1%	34.4%	0.5%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	783	510	-273	-34.9

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	0	8	8	Inf

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	6570	3577	-2993	-45.6

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	797	786	-11	-1.4

River Flow (5 Years Before and After Wildland Fire)

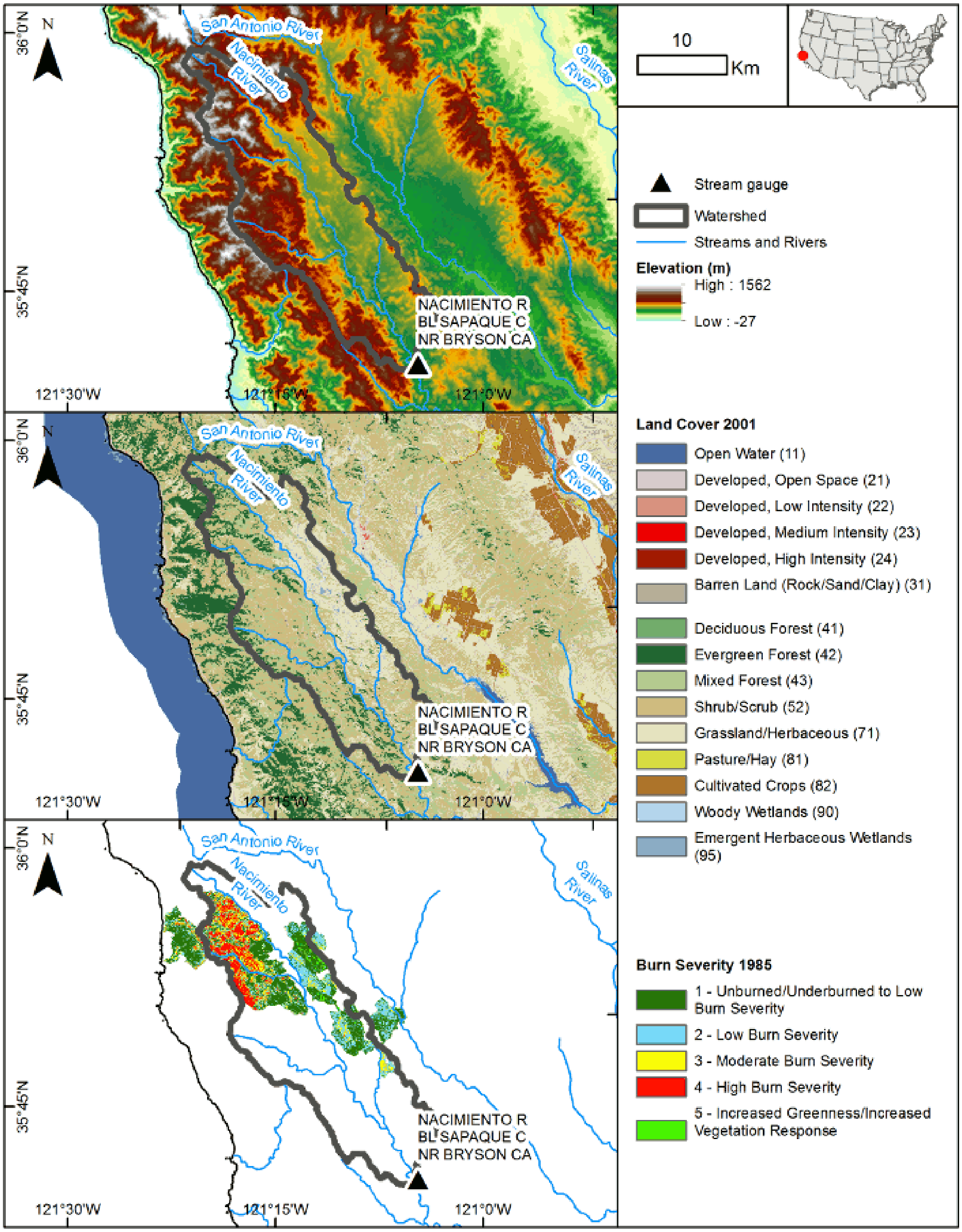
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	280	100	-180	-64.2

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM2	-182.0	2.0	-64.9	0.7

Nacimiento River near Bryson, California (Gauge 11148900)/1996 Unnamed Wildfire



Nacimiento River near Bryson, California

Water Resource Region: California (HUC-2 code 18) Climate Type (Köppen): Csb

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
11148900	35.788579 N	121.093805 E	403.5	2.32

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
276	1118	544	61.1	14.2

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	12%	22%	21%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
41%	1%	0%	4%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Unnamed	10/7/1996	Wildfire	128.9	32.0%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
14.7%	6.9%	5.4%	5.0%	0.4%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	937	934	-4	-0.4

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	2	0	-1	-94.8

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	19025	13697	-5328	-28.0

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	820	830	10	1.2

River Flow (5 Years Before and After Wildland Fire)

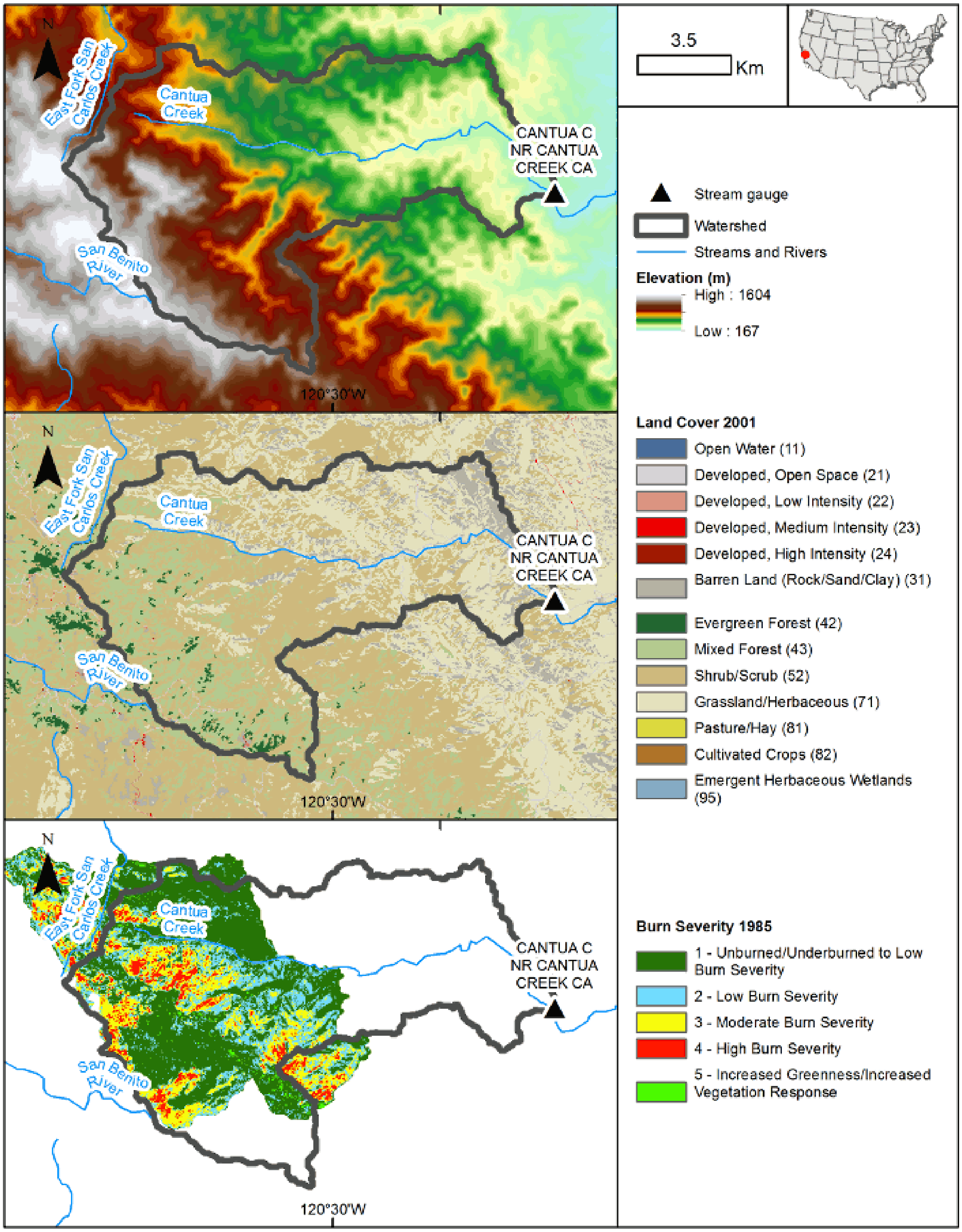
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	414	516	102	24.7

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM3	111.1	-9.0	26.8	-2.2

Cantua Creek near Cantua Creek, California (Gauge 11253310)/1985 Losgatosiv Wildfire



Cantua Creek near Cantua Creek, California

Water Resource Region: California (HUC-2 code 18) | Climate Type (Köppen): BWk

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
11253310	36.402174 N	120.433492 E	120.4	2.06

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
230	1510	759	56.8	17.7

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	1%	17%	30%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
42%	0%	0%	1%	8%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Losgatosiv	7/6/1985	Wildfire	63.5	52.7%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
30.7%	10.3%	9.8%	1.9%	0.1%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	525	320	-206	-39.2

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	88	172	84	95.6

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	2811	1459	-1352	-48.1

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	894	910	15	1.7

River Flow (5 Years Before and After Wildland Fire)

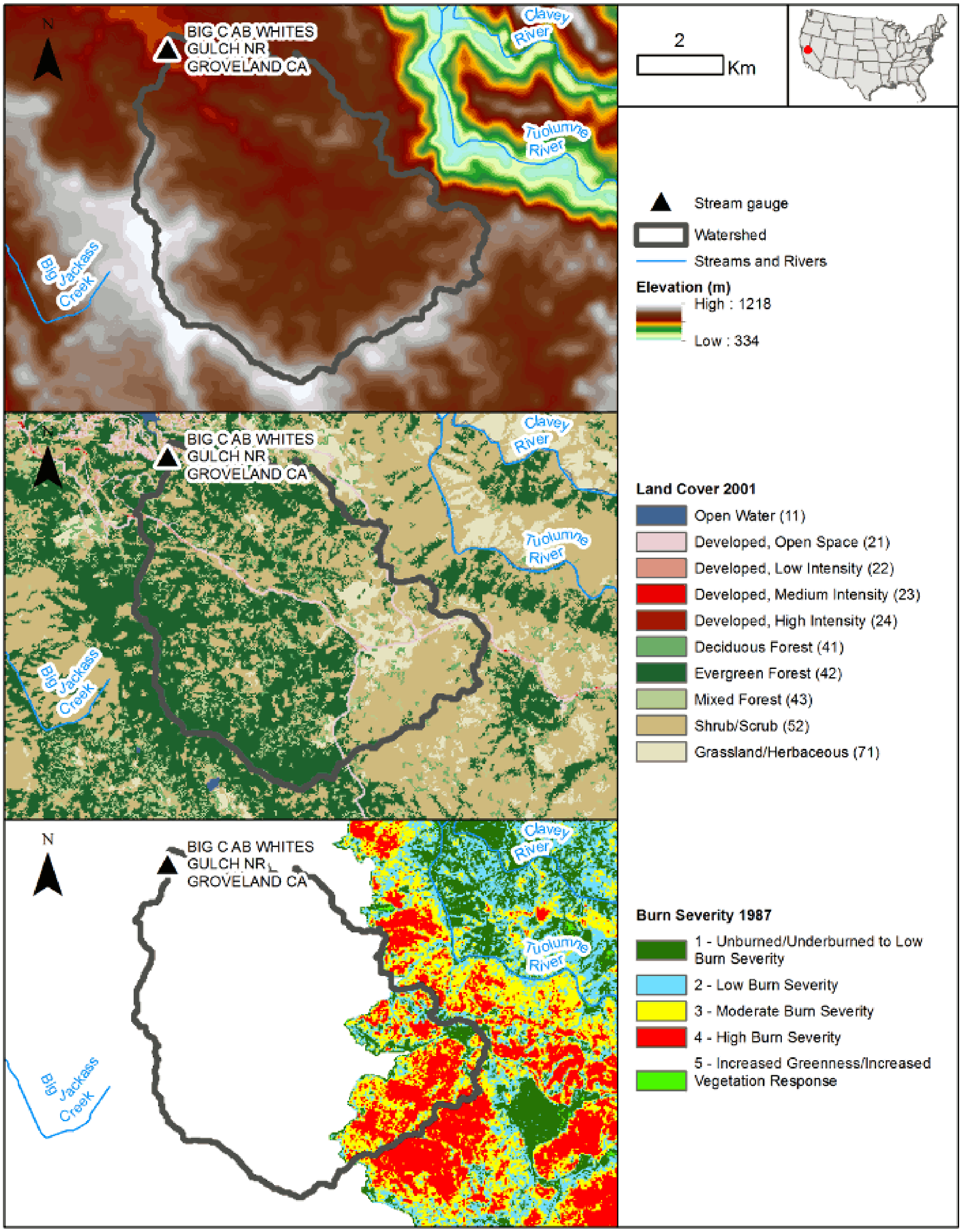
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	41	9	-32	-77.1

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM1	-45.1	13.6	-110.3	33.1

Big Creek near Groveland, California (Gauge 11284400)/1987 Hamm Wildfire



Big Creek near Groveland, California

Water Resource Region: California (HUC-2 code 18) — Climate Type (Köppen): Csa

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
11284400	37.841871 N	120.184910 E	41.7	1.68

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
806	1197	958	22.9	9.0

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
2%	47%	6%	6%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
36%	0%	0%	3%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Hamm	8/30/1987	Wildfire	8.6	20.6%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
3.9%	2.1%	7.8%	6.8%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1251	661	-590	-47.2

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	319	272	-47	-14.7

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	15363	5644	-9719	-63.3

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	730	747	17	2.3

River Flow (5 Years Before and After Wildland Fire)

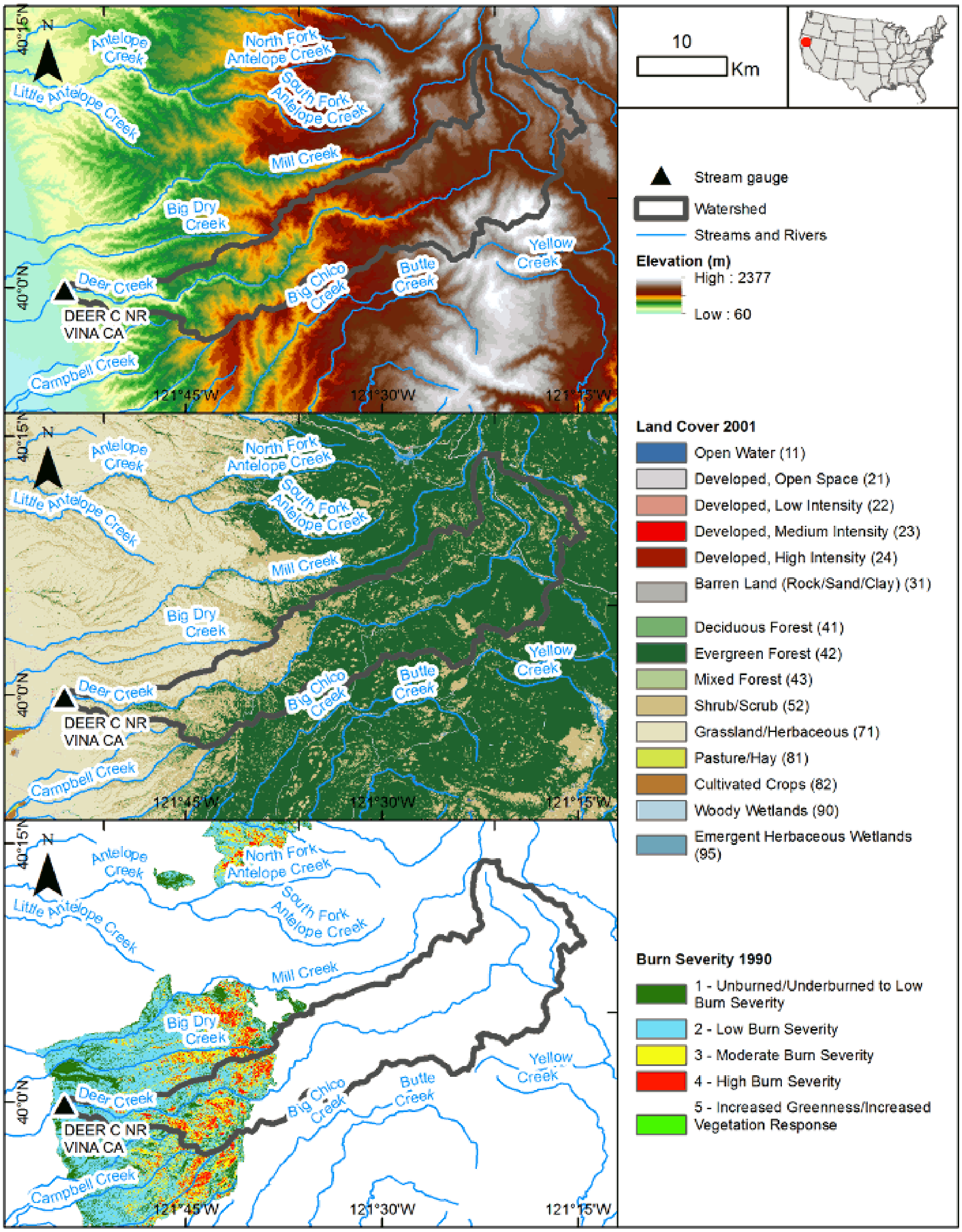
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	401	33	-368	-91.7

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM3	-315.5	-52.1	-78.7	-13.0

Deer Creek near Vina, California (Gauge 11383500)/1990 Campbell Wildfire



Deer Creek near Vina, California

Water Resource Region: California (HUC-2 code 18) Climate Type (Köppen): Csa

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
11383500	40.014047 N	121.948318 E	539.8	2.06

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
163	2351	1287	64.4	17.8

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
1%	67%	0%	9%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
21%	1%	0%	1%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Campbell	8/6/1990	Wildfire	116.0	21.6%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
2.7%	12.6%	4.3%	2.0%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1123	1106	-18	-1.6

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	3834	9315	5481	143.0

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	14992	11277	-3714	-24.8

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	638	642	4	0.6

River Flow (5 Years Before and After Wildland Fire)

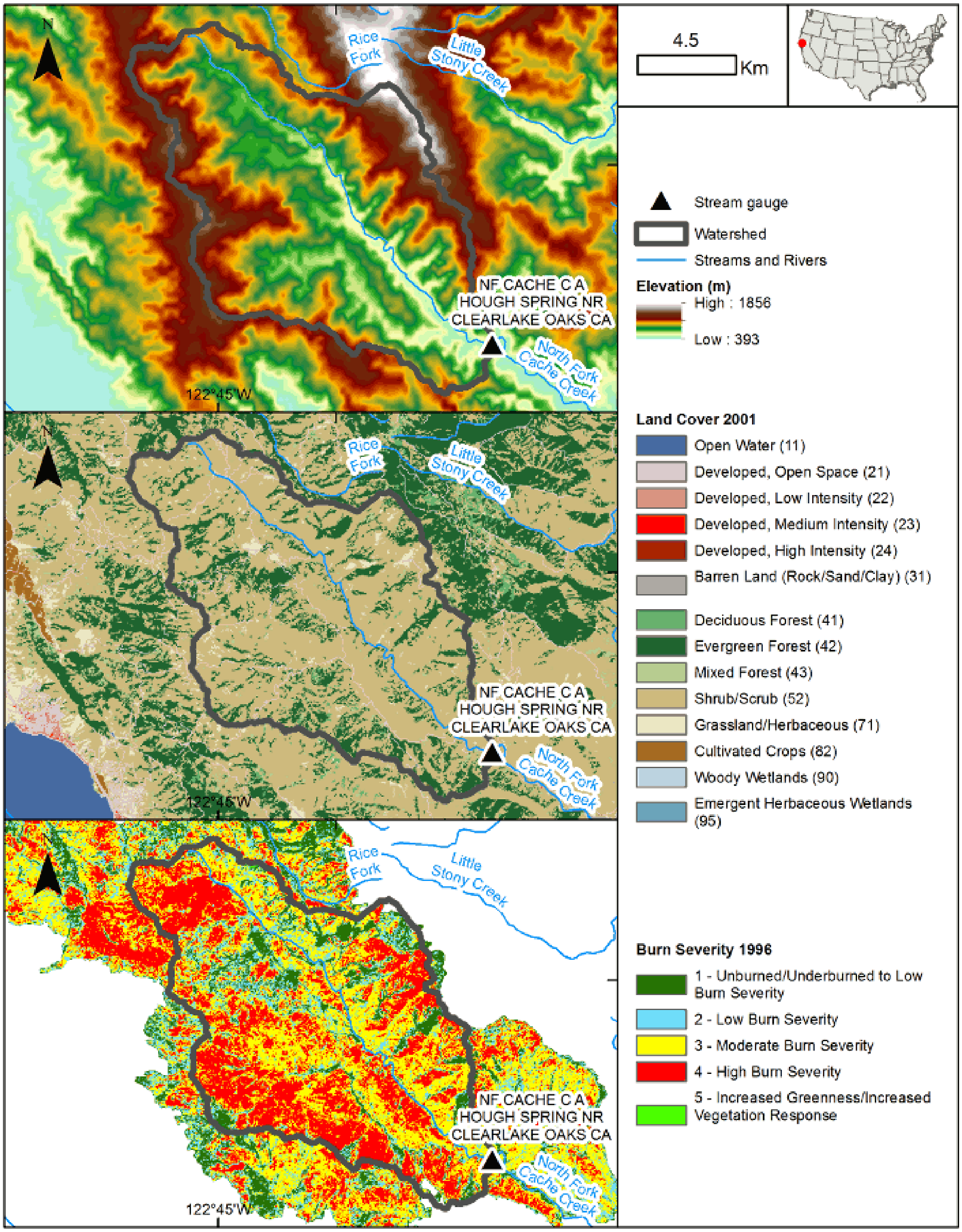
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	401	327	-74	-18.4

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM1	-12.5	-61.3	-3.1	-15.3

North Fork Cache Creek near Clearlake Oaks, California (Gauge 11451100)/1996 Fork Wildfire



North Fork Cache Creek near Clearlake Oaks, California

Water Resource Region: California (HUC-2 code 18) | Climate Type (Köppen): Csa

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
11451100	39.165446 N	122.619986 E	155.1	1.81

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
485	1776	910	55.9	23.7

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
0%	18%	2%	2%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
75%	0%	0%	2%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Fork	8/11/1996	Wildfire	154.3	99.6%

Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
11.0%	10.5%	43.5%	34.6%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1057	1275	218	20.7

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	22	19	-3	-13.8

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	21125	18822	-2303	-10.9

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	840	770	-70	-8.4

River Flow (5 Years Before and After Wildland Fire)

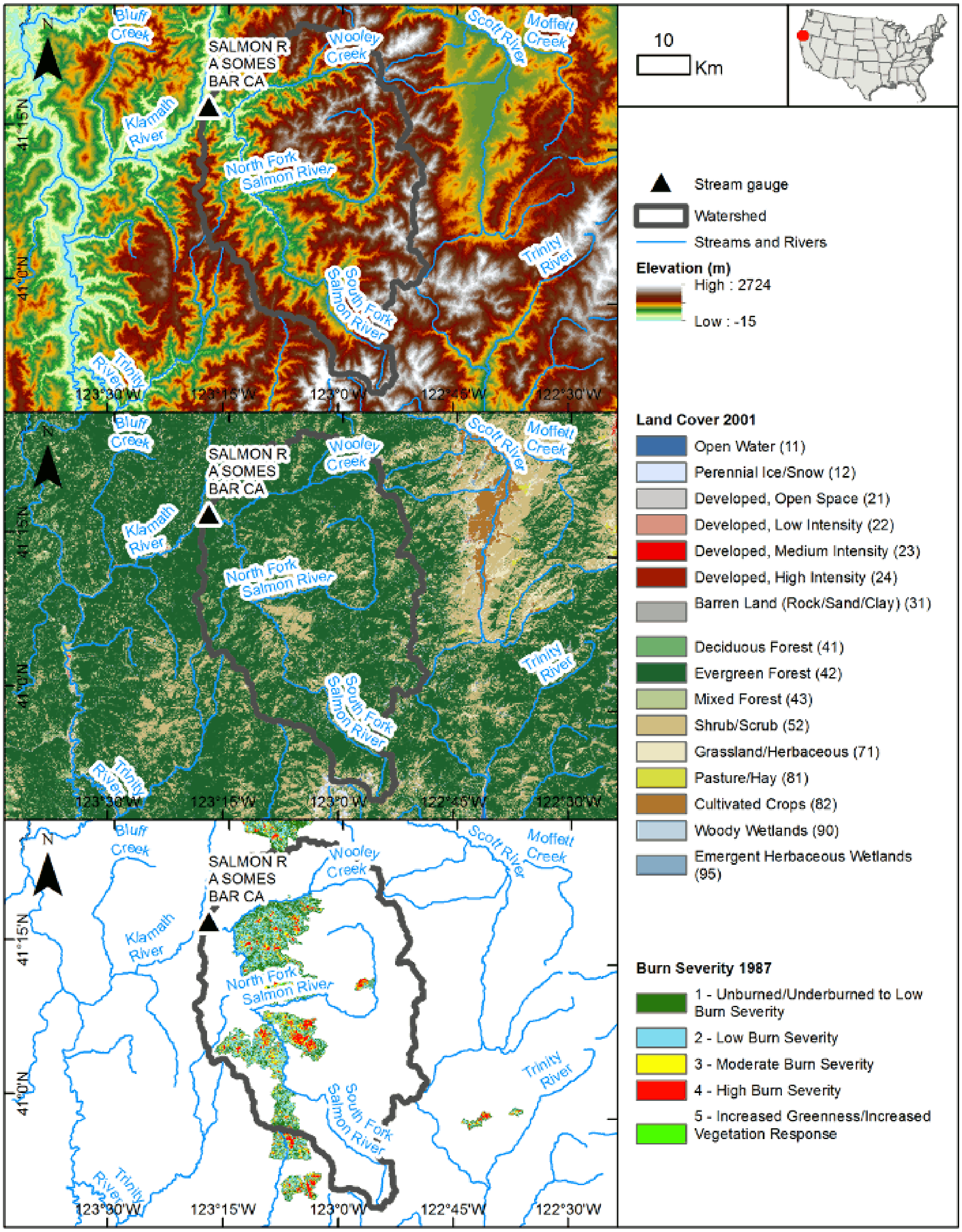
Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	678	918	240	35.4

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM3	103.3	136.4	15.2	20.1

Salmon River near Somes Bar, California (Gauge 11522500)/1987 Unnamed Wildfire



Salmon River near Somes Bar, California

Water Resource Region: California (HUC-2 code 18) Climate Type (Köppen): Csa

Gage Number	*Latitude*	*Longitude*	*Drainage Area (km^2)*	*Shape Parameter*
11522500	41.377627 N	123.477558 E	1943.1	1.89

Topography (GMTED2010)

Lowest Elevation (m)	*Highest Elevation (m)*	*Mean Elevation (m)*	*Maximum Slope (%)*	*Mean Slope (%)*
164	2570	1308	82.2	33.4

Land Cover (NLCD 2001)

Deciduous Forest	*Evergreen Forest*	*Mixed Forest*	*Grassland-Herbaceous*	*Cultivated Crop*
2%	76%	4%	1%	0%
Shrubland	*Wetland*	*Water*	*Developed*	*Barren*
15%	0%	0%	1%	0%

Wildland Fire (MTBS)

Name	*Date*	*Type*	*Burned Area (km^2)*	*Burned Area to Drainage Area Ratio (%)*
Various	8/30/1987	Wildfire	403.2	20.7%
Unburned-Underburned	*Low Severity*	*Moderate Severity*	*High Severity*	*Increased Greenness*
7.2%	9.2%	2.9%	1.4%	0.0%

Climate (5 Years Before and After Wildland Fire)

Annual Precipitation

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	1455	955	-500	-34.4

Annual Snow Water Equivalent

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	34892	4056	-30836	-88.4

Monthly Precipitation Variance

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
Daymet	15402	8059	-7343	-47.7

Annual Potential Evapotranspiration

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
PRISM	628	655	27	4.4

River Flow (5 Years Before and After Wildland Fire)

Annual River Flow

Source	*Pre-fire (mm)*	*Post-fire (mm)*	*Change (mm)*	*Change (%)*
GAGES-II	1064	512	-551	-51.8

Wildland Fire and Climate Contributions to Change in River Flow

Climate Elasticity Model	*Change Attributed to Climate (mm)*	*Change Attributed to Wildland Fire (mm)*	*Change Attributed to Climate (%)*	*Change Attributed to Wildland Fire (%)*
CEM1	-374.6	-176.7	-35.2	-16.6

APPENDIX C: LIST OF COMPLETED/PLANNED SCIENTIFIC/TECHNICAL PUBLICATIONS/SCIENCE DELIVERY PRODUCTS

Refereed Journal Articles

Hallema, D. W., Sun, G., Caldwell, P. V., Robinne, F.-N., Bladon, K. D., Norman, S. P., Liu, Y., Cohen, E. C. & McNulty, S. G. (2019). Wildland fire impacts on water yields across the Contiguous United States. U.S. Department of Agriculture Forest Service Southern Research Station, Gen. Tech. Rep. SRS-, Asheville, North Carolina.

Hallema, D. W., Robinne, F.-N., & Bladon, K. D. (2018). Reframing the challenge of global wildfire threats to water supplies. Earth's Future 6(6): 772-776.

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y., Bladon, K. D. & McNulty, S. G. (2018). Burned forests impact water supplies. Nature Communications 9:1307

Sun, G., Hallema, D. W. & Asbjornsen, H. (2017). Ecohydrological processes and ecosystem services in the Anthropocene: A review. Ecological Processes 6:35.

Hallema, D. W., Sun, G., Bladon, K. D., Norman, S. P., Caldwell, P. V., Liu, Y. & McNulty, S. G. (2017). Regional patterns of post-wildfire streamflow response in the Western United States: The importance of scale-specific connectivity. Hydrological Processes 31(14): 2582-2598.

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y., Ward, E. J. & McNulty, S. G. (2017). Assessment of wildland fire impacts on watershed annual water yield: Analytical framework and case studies in the United States. Ecohydrology, 10(2).

Hallema, D. W., Moussa, R., Sun, G. & McNulty, S. G. (2016). Surface storm flow prediction on hillslopes based on topography and hydrologic connectivity. Ecological Processes 5:13.

Conference Proceedings

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y. & McNulty, S. G. (2016). Relationships between wildland fire and watershed hydrology across the contiguous United States. In Stringer, C. E., Krauss, K. W. & Latimer, J. S. (Eds.), Headwaters to estuaries: Advances in watershed science and management. 5th Interagency Conference on Research in the Watersheds, North Charleston, South Carolina, March 2-5, 2015. U.S. Department of Agriculture Forest Service Southern Research Station, Gen. Tech. Rep. SRS-211, Asheville, North Carolina (p. 103). https://www.srs.fs.usda.gov/pubs/gtr/gtr_srs211/gtr_srs211_035.pdf

Web-Based Publications

CompassLive (Dennis Hallema & Stephanie Worley-Firley). Water Planning for the South in the New Fire Age. USDA Forest Service Southern Research Station, Asheville, North Carolina, 6/7/2016. http://www.srs.fs.usda.gov/compass/2016/06/07/water-planning-for-the-south-in-the-new-fire-age

USDA Southeast Regional Climate Hub (Dennis Hallema). Do Wildfires Affect Water Supplies? USDA Forest Service Southern Research Station, Raleigh, North Carolina, 4/28/2015. https://globalchange.ncsu.edu/serch/do-wildfires-affect-water-supplies

Recognition

Commendable Achievement (2017), Research Highlight 'Burning forests can impact water supplies', USDA Forest Service Southern Research Station, Director's Choice. https://srs.fs.usda.gov/research/2017-research-highlights

Invited Talks

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Robinne, F.-N., Bladon, K. D., Cohen, E. C., Liu, Y. & McNulty, S. G. (2018). Regional wildland fire threats to surface water supplies (Invited Seminar). Workshop 13, *Southern Blue Ridge Fire Learning Network*. Pickens, South Carolina, May 15-17, 2018.

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y. & McNulty, S. G. (2017). Étude de l'impact des feux de forêt et de la variabilité du climat sur les écoulements annuels des bassins versants des États-Unis (Invited Seminar). *Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture*, Antony, France, January 5, 2017.

Hallema, D. W. (2017). Proof that some, but not all wildland fires increase surface water supplies (Invited Seminar). First Friday All Climate Change Talks. *USDA Southeast Regional Climate Hub*, Raleigh, North Carolina, September 1, 2017.

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Mack, E. C., Liu, Y. & McNulty, S. G. (2016). Contributions of wildfire, drought and increased precipitation to regional streamflow patterns in the Western Cordillera (Invited Seminar). *USDA Forest Service Rocky Mountain Research Station*, Fort Collins, Colorado, September 7, 2016.

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Mack, E. C., Liu, Y. & McNulty, S. G. (2016). CONUS assessment of streamflow change in burned watersheds (Invited Seminar). *U.S. Geological Survey*, Boulder, Colorado, September 1, 2016.

Sun, G. & Hallema, D. W. (2016). Water resources and sustainable forest management in the Southeast (Invited Seminar). *Joseph W. Jones Ecological Research Center*, Newton, Georgia, March 22, 2016.

Hallema, D. W. (2016). Assessment of wildland fire impacts on streamflow in different regions of the U.S. (Invited Seminar). *Department of Forestry and Environmental Resources, North Carolina State University*, Raleigh, North Carolina, January 13, 2016.

Hallema, D. W., Sun, G., Norman, S. P., Caldwell, P. V., Mack, E. C., Liu, Y. & McNulty, S. G. (2015). Wildfire as a form of large-scale hydrologic disturbance in U.S. forests (Invited Seminar). Coweeta Lunch Seminar Series, *Coweeta Hydrologic Laboratory*, USDA Forest Service Southern Research Station, Otto, North Carolina, May 19, 2015.

Contributed Talks

Sun, G., Hallema, D. W., Caldwell, P. V., Norman, P. V., Cohen, E. C., Liu, Y., Bladon, K. D. & McNulty, S. G. (2018). Effects of wildland fires on CONUS streamflow. 5th International Conference on Forests and Water in a Changing Environment, *International Union of Forest Research Organizations*, Valdivia, Chile, November 5-9, 2018.

Sun, G., Hallema, D. W., Caldwell, P. V., Norman, S. P., Cohen, E., Liu, Y. & McNulty, S. G. (2017). Impacts of wildland fires on streamflow in the United States: Empirical evidence and modeling results. IUFRO17-2630, 125th Anniversary Congress, *International Union of Forest Research Organizations*, Freiburg, Germany, September 18-22, 2017.

Sun, G., Hallema, D. W., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y. & McNulty, S. G. (2017). After wildland fire, what happens to watershed water yield in the United States? COS 184-4, Annual Meeting, *Ecological Society of America*, Portland, Oregon, August 6-11, 2017.

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y. & McNulty, S. G. (2016). Wildland fire and climate variability impacts on annual streamflow in watersheds across the continental United States: Regional patterns and attribution analysis. H42A-07, 49th Fall Meeting, *American Geophysical Union*, San Francisco, California, December 12-16, 2016.

Hallema, D. W., Sun, G., Norman, S. P., Caldwell, P. V., Cohen, E. C., Liu, Y. & McNulty, S. G. (2015). Discussion of short and long term hydrologic effects of wildfire and associated management strategies in forests of the contiguous United States. 6th International Fire Ecology and Management Congress, *Association for Fire Ecology*, San Antonio, Texas, November 16-20, 2015.

Sun, G., Hallema, D. W., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y. & McNulty, S. G. (2015). Hydrological effects of wildfires across the contiguous United States: Field evidence and modeling results. Annual Water Resources Conference, *American Water Resources Association*, Denver, Colorado, November 17-19, 2015.

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y. & McNulty, S. G. (2015). Evaluation of complex relationships between large historic wildland fires and streamflow in watersheds across the conterminous United States. 4th International Conference on Forest and Water in a Changing Environment, *International Union of Forest Research Organizations*, Kelowna, British Columbia, July 6-9, 2015.

Posters Presented

Robinne, F.-N., Hallema, D. W., Sun, G. & Bladon, K. D. (2018). Global water security, wildfire risk, and society. P-1, Terrestrial Ecosystems and Agricultural and Forest Meteorology Symposium, *Nanjing University of Information Science and Technology*, Nanjing, Jiangsu Province, People's Republic of China, October 26-28, 2018.

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y., Bladon, K. D., Moussa, R. & McNulty, S. G. (2017). Contribution of wildland fires to water supply augmentation in the lower 48 United States. Postdoctoral Research Symposium, *North Carolina State University*, Raleigh, North Carolina, May 24, 2017.

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y. & McNulty, S. G. (2016). Attribution of multi-year streamflow changes to climate variability and fire disturbance. Postdoctoral Research Symposium, *North Carolina State University*, Raleigh, North Carolina, May 17, 2016.

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y. & McNulty, S. G. (2015). Empirical analysis and hydrological modeling of wildfire impacts on flow regimes in forest watersheds: Eastern vs. western United States. A51Q-0340, 48th Fall Meeting, *American Geophysical Union*, San Francisco, California, December 14-18, 2015.

Sun, G., Hallema, D. W., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y. & McNulty, S. G. (2014). Effects of wildfires and fuel treatment strategies on water quantity across the contiguous United States. H51I-0720, 47th Fall Meeting, *American Geophysical Union*, San Francisco, California, December 15-19, 2014.

Media Coverage

KJZZ News (Nicholas Gerbis). Radio interview. Southwest wildfires boost stream flows. Phoenix, Arizona, 4/10/2018. https://kjzz.org/content/633660/study-southwest-wildfires-boost-stream-flows

Terra Daily. Large wildfires bring increases in annual river flow. Corvallis, Oregon, 4/16/2018. http://www.terradaily.com/reports/Large_wildfires_bring_increases_in_annual_river_flow_999.html

Phys.org (Steve Lundeberg). Large wildfires bring increases in annual river flow. 4/13/2018. https://phys.org/news/2018-04-large-wildfires-annual-river.html

Science Daily (Oregon State University). Large wildfires bring increases in annual river flow. 4/13/2018. https://www.sciencedaily.com/releases/2018/04/180413093845.htm

Laboratory Equipment (Oregon State University). Large wildfires bring increases in annual river flow. 4/13/2018. https://www.laboratoryequipment.com/news/2018/04/large-wildfires-bring-increases-annual-river-flow

KTVZ News Channel 21. Study: Big wildfires boost river flows for years. Corvallis, Oregon, 4/13/2018. http://www.ktvz.com/news/study-big-wildfires-boost-river-flows-for-years/729191892

EurekAlert! New release. Large wildfires bring increases in annual river flow. Corvallis, Oregon, 4/12/2018. https://www.eurekalert.org/pub_releases/2018-04/osu-lwb041218.php

Oregon State University (Steve Lundeberg). Large wildfires bring increases in annual river flow. Corvallis, Oregon, 4/12/2018. http://today.oregonstate.edu/news/large-wildfires-bring-increases-annual-river-flow

Nature Asia. Press release. Earth sciences: Wildfires impact river flow in the contiguous USA. 4/11/2018. https://www.natureasia.com/en/research/highlight/12456

Deutschlandfunk Forschung Aktuell (Monika Seynsche). Radio interview. Das Leiden des Wassers (The suffering of the water, in German). 102nd Annual Meeting of the Ecological Society of America. Portland, Oregon, 8/9/2017. http://www.deutschlandfunk.de/waldbraende-das-leiden-des-wassers.676.de.html?dram:article_id=392996

Canadian Broadcasting Corporation: Daybreak South (Chris Walker). Live radio interview. 4th International Conference on Forest and Water in a Changing Environment. Kelowna, British Columbia, Canada, 7/8/2015. http://www.srs.fs.usda.gov/compass/2015/08/27/a-conversation-about-fire-and-water

Other Mentions

Boreal Water Futures Newsletter (François-Nicolas Robinne). Reframing the challenge of global wildfire threats to water supplies. School of Geography & Earth Sciences, McMaster University, Hamilton, Canada, 11/11/2018.

Southern Blue Ridge Fire Learning Network Workshop 13 (Beth Buchanan). 13 Isn't Unlucky for Southern Blue Ridge FLN. Southern Blue Ridge Fire Learning Network, Durham, North Carolina, 6/20/2018. https://conservationgateway.org/ConservationPractices/FireLandscapes/FireLearningNetwork/USFLNPublications/Documents/136-NotesFromTheField_SBR-workshop-2018.pdf

CompassLive (Patty Matteson). Megafires, wildland fires, and prescribed burns. USDA Forest Service Southern Research Station, Asheville, North Carolina, 5/10/2018. https://www.srs.fs.usda.gov/compass/2018/05/10/megafires-wildland-fires-and-prescribed-burns

Eastern Forest Environmental Threat Assessment Center (Stephanie Worley-Firley). Burning forests impact water supplies. USDA Forest Service Southern Research Station, Asheville, North Carolina, 4/20/2018. https://forestthreats.org/news/in-the-news/burning-forests-impact-water-supplies

USDA Forest Service Southern Research Station (Patty Matteson). Burned forests impact water supplies. News release. Asheville, North Carolina, 4/16/2018. https://www.srs.fs.usda.gov/news/649

CompassLive (Stephanie Worley-Firley). After the fire, what happens to water yield? USDA Forest Service Southern Research Station, Asheville, North Carolina, 12/15/2016. http://www.srs.fs.usda.gov/compass/2016/12/15/after-the-fire-what-happens-to-water-yield

CompassLive (Stephanie Worley-Firley). A conversation about fire and water: Research fellow rides the Canadian airwaves during international conference. USDA Forest Service Southern Research Station, Asheville, North Carolina, 8/27/2015. http://www.srs.fs.usda.gov/compass/2015/08/27/a-conversation-about-fire-and-water

CompassLive (Stephanie Worley Firley). How do wildfires and efforts to abate them affect the nation's water supplies? USDA Forest Service Southern Research Station, Asheville, North Carolina, 10/16/2014. https://www.srs.fs.usda.gov/compass/2014/10/16/how-do-wildfires-and-efforts-to-abate-them-affect-the-nations-water-supplies/

APPENDIX D: METADATA

Data are available from the Forest Service Research Data Archive:

Hallema, D.W.; Sun, G.; Caldwell, P.V.; McNulty, S.G. 2019. Wildland fire impacts on water supply (FIWAS) data for the contiguous United States. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2019-0012

We collected data for 168 locations across the contiguous United States (CONUS) affected by wildland fire during the period 1984 - 2013. Wildland fire locations, dates, extent, and burn severity were obtained from the Monitoring Trends in Burn Severity (MTBS) dataset. We obtained watershed attributes (watershed boundaries, drainage areas, and perimeters) and daily time series of river flow from the GAGES-II dataset (Geospatial Attributes of Gages for Evaluating Streamflow, version II). The boundaries of the water resource regions were acquired from the Watershed Boundary Database. Climate data were extracted from the daily high resolution (1 × 1 km) Daymet v3 dataset, and obtained the gridded PRISM (Parameter-elevation Regressions on Independent Slopes Model) dataset. For topographic data (elevation, slope, and aspect), we used the highest resolution version (244 × 244 m) of the Global Multi-resolution Terrain Elevation Data 2010, principally obtained during the Shuttle Radar Topography Mission. Finally, we obtained land cover data from the 2001 National Land Cover Database (NLCD).