SAN FRANCISCO
ESTUARY & WATERSHED SCIENCE
Sponsored by the Delta Stewardship Council and UC Davis Institute of the Environment

THE STATE OF BAY-DELTA SCIENCE 2025

# Recent Findings and Future Prospects for Water Quality Effects from Catastrophic Wildfires in California, USA

Clifford N. Dahm*[1], Denise D. Colombano[2], Randy A. Dahlgren[3]

## ABSTRACT

Global change affects the forests and wildlands of California through rising temperatures, earlier snowmelt, more rain and less snow, greater vapor-pressure deficits, and forest dieback, resulting in increased frequency, size, and severity of wildfires. California has experienced its eight largest wildfires since 1932 in the period from 2018 to 2024. The largest fire to date (August Complex Fire) occurred in 2020—a year in which 1.7 million ha or 4% of California's land area burned—and burned 418,000 ha. These mega-fires (>10,000 ha) can severely affect water quality and aquatic ecosystems. Water-quality variables affected by wildfire include temperature, sediment load, turbidity, dissolved oxygen, pH, redox potential, soluble and particulate organic carbon, nutrients, metals, natural- and human-produced organic contaminants, and primary/secondary producers. Wildfire and water interact at watershed scales, with water-quality impairments responding linearly with the percentage of the watershed area burned, and responding exponentially as burn severity increases. Vegetation recovery is key to the duration of water-quality effects, and short-term, post-fire weather dictates actual water-related effects. Urban areas are hot spots for the production and transport of water pollutants such as sediments, heavy metals, mercury, nutrients, and toxic organic compounds. Water-treatability challenges after wildfire include short-term odor and taste, increased sediment and turbidity, and increased total and dissolved organic matter. Implications for water quality from catastrophic wildfire on downstream reservoirs are important research needs because ~80% of California's water supply passes through reservoirs before use. Notably, there is a crucial need for development and assessment of post-fire, land-management practices to mitigate adverse water-quality effects. Finally, continuous measurements of water quality are critical to document the severity and duration of episodic pulses of wildfire-sensitive constituents that are mobilized and transported to aquatic ecosystems after catastrophic mega-fires.

**SFEWS Volume 23 | Issue 3 | Article 2**
*https://doi.org/10.15447/sfews.2025v23iss3art2*

* Corresponding author:

1 University of New Mexico
Albuquerque, NM 87131 USA

2 Delta Stewardship Council, Delta Science Program
Sacramento, CA 95814 USA

3 University of California–Davis
Davis, CA 95616 USA

## KEY WORDS

mega-fires, water quality, hydrology, streams, reservoirs, warming climate, wildfire recovery, continuous monitoring, extreme events

## INTRODUCTION

Catastrophic mega-fires are surging in frequency, severity, and extent around the world and throughout the western US (Ball et al. 2021; Bowman and Sharples 2023; Nichols et al. 2024). Such wildfires have been observed in Australia's forests and bushlands (~24 million hectares (ha) burned in 2019–2020); the Pantanal, South America's largest tropical wetland (~2.35 million ha or ~12% of the total area burned in 2020); and across Canada (~18 million ha or ~5% of total area burned in 2023) (Robinne et al. 2021; Neto and Evangelista 2022). Catastrophic wildfires in the forests of California, US, are also on the rise: the eight largest fires since 1932 occurred from 2018 to 2024, ranged in size from 129,100 to 418,000 ha, and burned a total area of ~1.7 million ha (Table 1). These wildfires exceeded the criteria for being called a "mega-fire" or one that burns greater than 10,000 ha of land (equivalent to 24,711 acres) (Linley et al. 2022). Because catastrophic mega-fires have become a more prevalent recent phenomenon, and new and more destructive wildfires are occurring almost every year, our collective understanding of the extent and severity of socio-economic and ecological effects is rapidly developing.

Long-term trends show that the frequency and severity of wildfires in the western US increased abruptly in the mid-1980s (Westerling 2016), likely because of regional climate changes such as rising temperatures, earlier snowmelt, more rain and less snow, greater vapor-pressure deficits in spring and autumn, and forest dieback. In northern California, data show that wildfires are becoming more frequent, and their intensity and the area they burn are also increasing (i.e., hotter fires), and the fire season duration is more than 2 months longer (Keeley and Syphard 2021; Safford et al. 2022; Western Fire Chiefs Association c2022). In southern California, the fire season is now year-round (Western Fire Chiefs Association c2022). Dennison et al. (2014) found that trends for large wildfire in the western US from 1984 to 2011 included an increase in large fires (>405 ha) of seven fires per year, and the total fire area increased at a rate of 355 $km^2$ per year. Williams et al. (2019) showed that California's annual wildfire extent increased 5-fold from 1972 to 2018, with human-caused warming already significantly enhancing wildfire in California, particularly in the forests of the Sierra Nevada and North Coast. The largest California fire to date—the August Complex wildfire—occurred in August of 2020 and burned 418,000 ha, and the second-largest fire to date—the Dixie wildfire—occurred in July of 2021 and burned 389,800 ha (Table 1). Notably, wildfires in 2020 and 2021 burned a greater areal extent than all the other largest fires from 1932 to 2019 combined (Figure 1).

**Table 1** Eight largest mega-fires in California recorded history; all eight of these wildfires have occurred in the Delta watershed since 2018 (see Figure 1). The total area burned by these eight mega-fires is 1,176,000 hectares. *Source: CALFIRE.*

| Fire name | Date | Counties | Hectares |
|---|---|---|---|
| August Complex | Aug 2020 | Mendocino, Humboldt, Trinity, Tehama, Glenn, Lake, Colusa | 418,000 |
| Dixie | Jul 2021 | Butte, Plumas, Lassen, Shasta, Tehama | 389,000 |
| Mendocino Complex | Jul 2018 | Colusa, Lake, Mendocino, Glenn | 186,000 |
| Park | Jul 2024 | Butte, Plumas, Shasta, Tehama | 173,900 |
| SCU Lightning Complex | Aug 2020 | Stanislaus, Santa Clara, Alameda, Contra Costa, San Joaquin | 160,500 |
| Creek | Sep 2020 | Fresno, Madera | 154,000 |
| LNU Lightning Complex | Aug 2020 | Napa, Solano, Sonoma, Yolo, Lake, Colusa | 147,000 |
| North Complex | Aug 2020 | Butte, Plumas, Yuba | 129,100 |

The social and ecological effects of water-quality impairments associated with such large and destructive wildfires are a major concern because of the high demand for water from biodiversity conservation as well as residential, municipal, and agricultural consumptive uses. Researchers are increasingly documenting the spatial extent of effects on watersheds. For example, Ball et al. (2021) show that over the last 3 decades, the cumulative effect of wildfires on rivers and streams—both within burn scars and extending beyond burn scars into downstream networks—

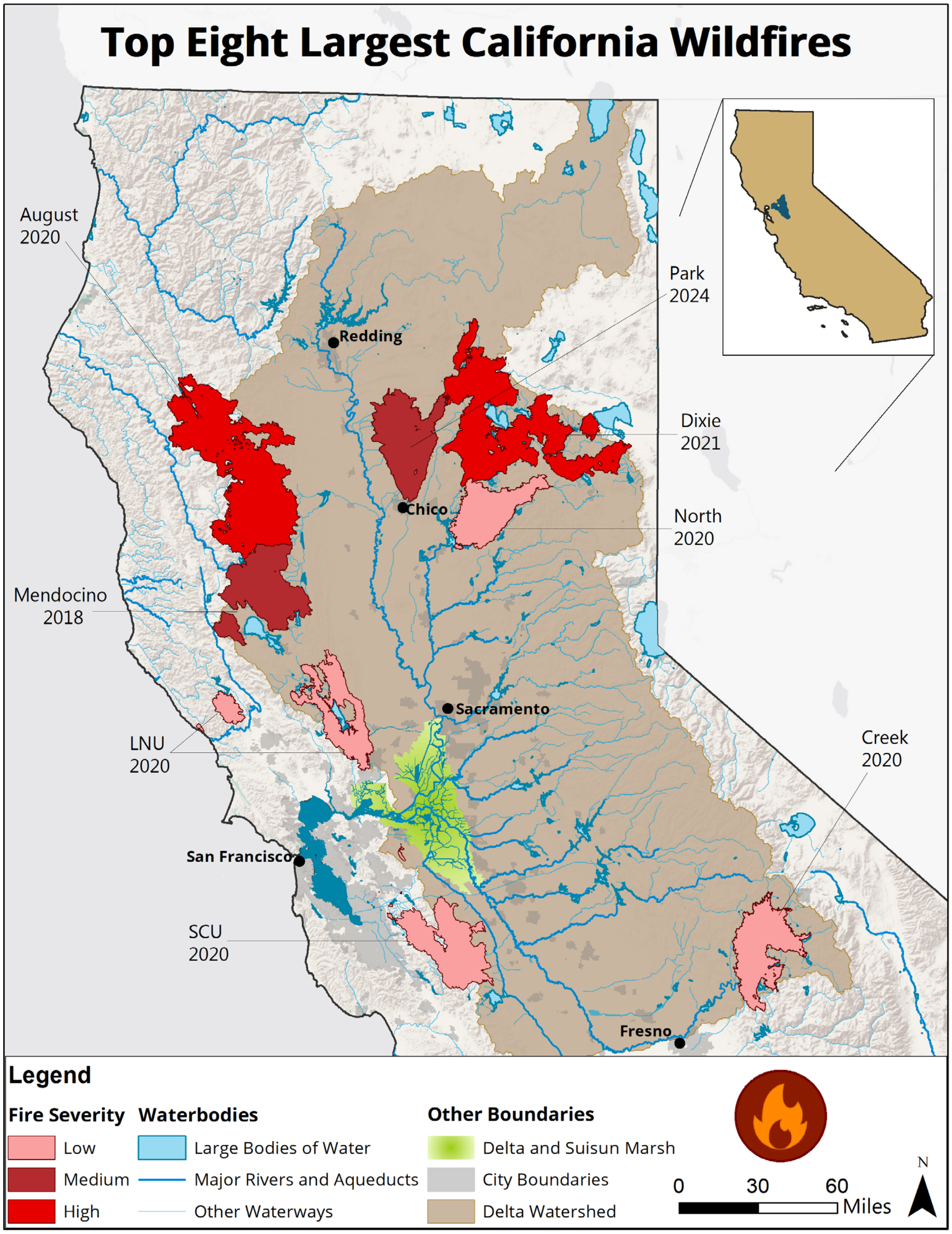


**Figure 1** Map of the Sacramento and San Joaquin catchments that flow into the California Delta. Locations of the eight largest mega-fires within various catchments are shown. All eight mega-fires have occurred between 2018 and 2024. Other features that are shown include the extent of low, moderate, and high-intensity wildfires associated with each mega-fire, major rivers and aqueducts, lakes and reservoirs, large cities, the Delta and Suisun Marsh, and major city boundaries. *Sources: CAL FIRE and partners including USDA Forest Service Region 5, USDI's Bureau of Land Management, National Park Service, National Fish and Wildlife Service, and numerous local agencies (2024); Wildland Fire Interagency Geospatial Services Group data products under the interagency Wildland Fire Data Program, hosted in the National Interagency Fire Center (201`24); USGS National Hydrography Dataset (2024); Wetlands and Water Resources (2011); Watershed Boundary Dataset provided by the USDA-NRCS, USGS and EPA (2024); US Census Bureau (2018); Delta Stewardship Council (2024); and ESRI ArcGIS Desktop 10.8. Image credit: Megan Thomson.*

scales up to 11% of the total stream and river length in the western US. In addition, researchers are studying the severity and duration of episodic pulses of wildfire-sensitive constituents (e.g., sediments, nutrients, metals, and organic contaminants) mobilized and transported to aquatic ecosystems and municipal water supplies (Chow et al. 2021), drinking-water contamination (Solomon et al. 2021), aquatic-habitat degradation (Elliott et al. 2024), disruption of hydrological and erosional processes (Nunes et al. 2018), and fish kills in downstream aquatic habitats (Reale et al. 2021).

The overall goals of this paper are to review recent water-quality studies in California aquatic ecosystems (streams, rivers, reservoirs, and lakes) affected by catastrophic wildfire, and to discuss implications of changing fire regimes on California water resources. We emphasize California's largest watershed—the Sacramento–San Joaquin River Delta (hereafter "Delta")—which receives approximately 40% of the state's river and stream discharge, serves as the hub for the state's water supply system, and supports thousands of resident and migratory species of fish and wildlife (Figure 1; Luoma et al. 2015). We also provide a list of useful metrics from existing literature that can be used as indicators of wildfire effects on water quality. The metrics fall into two general categories. First are variables affecting the extent of wildfire effects on water quality. These include fire size (percentage of watershed area burned), fire intensity (vegetative death and soil cover), urban and suburban areas burned (impervious surfaces and pollutant sources), and vegetation recovery (fire adaptability and coniferous/deciduous structure). Second are variables reflecting realized water-quality effects that are linked to post-fire weather and climate, such as the amount of precipitation, the timing of precipitation, and the type of precipitation (e.g., snow vs. rain). Finally, we summarize key points from our review, and offer thoughts on future research and monitoring needs for the Delta watershed, which is projected to experience a prevalence of hotter and more combustible mega-fires under future climate change.

## SEVERE WILDFIRES: WATER-QUALITY EFFECTS

### Overview of Wildfire Effects on Water Quality

Smith et al. (2011) reviewed how large wildfires affected global water quality in forested catchments, focusing on implications for water supply. This review paper provides a good summary of how wildfires affect water quality for published studies up through about 2010. Topics discussed in the Smith et al. (2011) paper include suspended sediment, wildfire ash, nitrogen (N) and phosphorus (P), trace elements, chloride (Cl), sulfate (SO4), and sodium (Na), organic carbon, cyanide, and a few organic contaminants (e.g., polycyclic aromatic hydrocarbons [PAHs] and polychlorinated biphenyls [PCBs]). We will take a broader look at water-quality contaminants, focusing primarily on dissolved and particulate contaminants of concern after severe wildfires throughout California since 2010.

Lakes/reservoirs located downwind of major wildfires often receive particulate matter and adsorbed pollutants via atmospheric deposition that can degrade water quality (Sanders et al. 2022). There is a paucity of information concerning the potential effects to these lentic ecosystems from atmospheric deposition from mega-fires. For example, an analysis of lake sediments in a sub-arctic boreal forest found that metals (e.g., Pb, Hg, Al, and Fe), and metalloids (As and Sb) were elevated during wildfire periods, but only by a small amount (Pelletier et al. 2020). In terms of nutrients, Koplitz et al. (2021), using an atmospheric chemistry modeling approach, suggested maximum N and S deposition rates of 1.4 kg N $ha^{-1}$ $yr^{-1}$ and 0.6 kg S $ha^{-1}$ $yr^{-1}$ in the Pacific Northwest, US. This represented over ~30% of total atmospheric deposition in some areas. Another modeling study focused on the historic 2020 fire season in California, and posited that total N deposition for mixed forest types in California averaged from August–October 2020 increased from 6.2 to 16.9 kg $ha^{-1}$ $yr^{-1}$, a relative increase of up to ~173% (Campbell et al. 2022). Thus, the potential for atmospheric deposition, while short-lived from an individual fire, could be substantial during prolonged periods of elevated [increased?] widespread wildfire activity. Atmospheric smoke was also shown to reduce

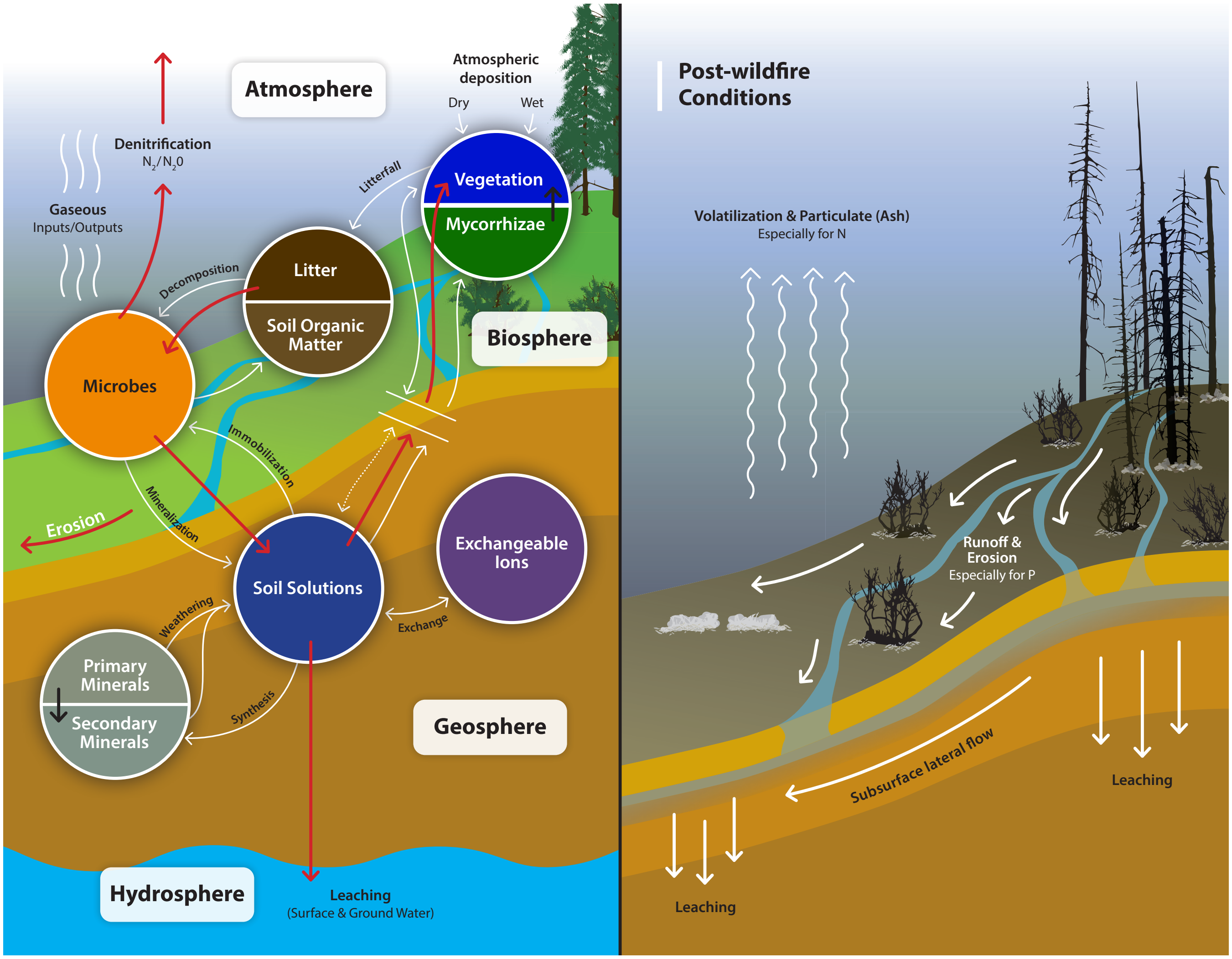


**Figure 2** Major biogeochemical processes in the atmosphere, biosphere, geosphere, and hydrosphere of an unburned catchment in the *left panel*, and post-wildfire conditions in the catchment after a mega-fire in the *right panel*. Recovery of the burned catchment post-wildfire is crucial to the recovery of water quality after major wildfires.

ultraviolet-B (UV-B) radiation, photosynthetically active radiation (PAR), and lake heat content, thereby altering primary production and changes in foodweb dynamics (Scordo et al. 2021; Scordo et al. 2022). We identify atmospheric deposition and smoke effects that originate from wildfires as an important area for future water-quality and aquatic-ecosystem research, especially in regard to sensitive, high-elevation lentic ecosystems (e.g., Farruggia et al. 2024 and Smits et al. 2024).

Runoff/erosion is typically the major contributor to downstream water-quality impairments after wildfires, because of the large increases in surface runoff associated with the loss of soil cover (Bixby et al. 2015; Murphy et al. 2018; Uzun et al. 2020; Figure 2). Water-quality effects tend to increase exponentially as the burn severity within a watershed increases, because of the extensive loss of vegetation/soil cover (Uzun et al. 2020). For example, a severely burned area may experience massive debris flows, whereas less severely burned areas may predominantly experience less damaging sheet and rill erosion, which downslope vegetated patches may attenuate. Moreover, adverse water-quality effects increase in a linear manner as the percentage of the burned watershed increases. This results from the additive effect of increasing burned source area and a decreasing dilution effect from non-burned areas within the watershed. Thus, as wildfires become larger and more severe, water quality will be more severely affected.

The major water pollutants that originate from surface runoff will include a major pulse of water-soluble constituents leached from the surficial ash layer, and a pronounced increase in suspended sediments and constituents attached to the particles. The major soluble constituents include total dissolved solids (TDS), Na, K, Ca, Mg, $HCO_3$, $SO_4$, Cl, $NO_3$, $NH_4$, $PO_4$, DOC, Mn, Zn, and Fe (Paul et al. 2022). While suspended sediments can severely degrade aquatic habitats and organisms, the majority of the components that comprise suspended sediments are relatively insoluble. However, suspended sediments can undergo sorption/desorption reactions and precipitation/dissolution reactions that transfer elements between the soluble and solid phases. Phosphorus, organic carbon and nitrogen, heavy metals/metalloids, polyaromatic hydrocarbons, and mercury are notable constituents contained in the suspended sediment fraction. While these constituents are generally not damaging/toxic in the forest environment, they may cause impairments when incorporated into anoxic sediments in downstream water bodies. For example, (1) nutrients (N and P) may contribute to eutrophication, (2) organic matter may contribute to biological oxygen demand and oxygen depletion, (3) redox-sensitive species (e.g., Fe, Mn, As, Cr, S) in sediments may be released to the water column, and (4) mercury may be released from particulate matter and undergo methylation reactions in lentic environments.

Pyromineralized solutes that originate from the surface ash layer and heated surface soils may enter surface waters via sub-surface lateral flow-paths or deeper groundwater flow-paths. Many low- to mid-elevation forest soils in California have a clay-rich horizon (Bt – argillic horizon) at 30- to 50-cm depths that creates a perched water table that initiates subsurface lateral flow through topsoil horizons during larger rainfall events (Swarowsky et al. 2012). Physical filtration along this flow-path removes particulate bound constituents, but soluble constituents (e.g., major cations and anions, NO3-, DOC, DON) can be rapidly delivered to surface waters during storms (Swarowsky et al. 2012). Some of these constituents may also enter deeper groundwater flow-paths where their composition is attenuated/altered (e.g., DOC/DON sorption/decomposition; denitrification) before they are discharged to surface waters with a time lag (months to years) (McDowell et al. 2021). Figure 2 shows a conceptual model of the various mechanisms by which water-quality impairments are routed to surface water.

Another appreciable source of solutes to surface waters comes from enhanced microbial mineralization of soil organic matter, and the role of increasing fire severity on soil microbial communities after wildfires (Dove et al. 2022). Wildfires decouple microbial functional associations within soil C–N–P cycling processes, which leads to nutrient imbalances (e.g., excess P) that contribute to ecosystem losses of nutrients (Shen et al. 2024, 2025). Shifts in microbial communities slowly recouple the integrated nutrient cycles over time (decadeal time-scale) to tighten the overall nutrient cycle, thereby limiting ecosystem nutrient losses. Further, severe mega-fires kill the majority of vegetation, and it requires several years to decades to regenerate the vegetation in conifer-dominated forests. In the absence of vegetation, the plant uptake step of the nutrient cycling process is broken, similar to that found after forest clear-cutting (Dahlgren and Driscoll 1994; Vitousek et al. 1979, Figure 2). As a result, the mineralized nutrients accumulate in soil solution, where they can subsequently be leached to surface/ground waters. Moreover, the loss of vegetation results in warmer (no canopy cover) and wetter (decreased evapotranspiration [ET]) soils that greatly increase microbial activity and the mineralization of nutrients from organic matter. Thus, there is potential for a long-term loss of nutrients to surface waters while forests are regenerating and microbial communities are recovering. Larger and more severe fires will clearly exacerbate this recovery period, leading to longer-term water-quality effects. Conversely, in areas where vegetation recovery is rapid (e.g., California Coastal Ranges' chaparral ecosystems), enhanced post-fire microbial mineralization will accelerate vegetation recovery by providing a short-term fertilization effect, as stump-sprouting vegetation can immediately uptake nutrients through their non-damaged rooting system. Thus, the longer-term water-quality effects from mineralization of soil organic matter are largely a function of the speed of vegetation recovery (Rother et al. 2022).

In summary, the *potential* for adverse wildfire effects on water quality is set by the percentage of the watershed area burned, and the severity of the wildfire (the degree of fire-induced change to vegetation and soils 1 year post-fire; Parks et al. 2016). However, post-fire weather dictates *actual* water quality effects by influencing the runoff/leaching volume and hydrologic flow-path (i.e., surface runoff, sub-surface lateral flow, groundwater recharge). Post-fire weather factors that affect water-quality effects include the amount and intensity of precipitation, the seasonal timing of precipitation and snow vs. rain forms of precipitation. For example, the Park Fire started on July 24, 2024, and became the fourth-largest California wildfire at 173,900 hectares. Burn scar precipitation in August and November of 2024 degraded water quality and negatively affected the spring run salmon. Conversely, low rainfall years after the Angora Fire (2007), Rim Fire (2013) and Rocky and Wragg fires (2015) resulted in low watershed runoff, which limited the transport of waterborne pollutants (Oliver et al. 2012; Wang et al. 2016; Uzun et al. 2020). Similarly, areas that receive a large fraction of their precipitation as snowfall are less susceptible to pollutant transport because the slow melting of snow generally does not generate widespread surface runoff/erosion; rather, melt waters largely percolate into the soil, where physical filtration and water–soil interactions retain several pollutants. Finally, urban/suburban/exurban areas are potential "hot-spots" for generation of water-quality contaminants (Alshehri et al. 2023; Magliozzi et al. 2024). These populated areas are both a source of myriad pollutants (e.g., sediments, heavy metals, mercury, nutrients, toxic organics – PAHs, benzene, electronic and plastic pollutants, oil/grease, pesticides, and pharmaceuticals) and their large proportion of impermeable surface area leads to greater runoff/erosion and pollutant transport. Many of these pollutants can be transiently retained in riparian zones and stream sediments, or percolate into the groundwater system where they can induce lingering surface water-quality effects for several years.

### Real-Time Monitoring and Remote Sensing Applications to Assess Post-Fire Water Quality

Given the nature of the Mediterranean climate in California (water feast vs. famine), the majority of pollutant transport (or load) occurs during a few large storms each winter (Dettinger et al. 2011). Within a given storm event, concentrations of water-quality constituents can change by several orders of magnitude (Dahlgren et al. 2005). Hence, after a major watershed disturbance such as wildfires, it becomes necessary to collect frequent water-quality measurements to fully assess perturbation effects. Similarly, several biologically important water-quality constituents (e.g., DO, pH, conductivity, chlorophyll, temperature) display appreciably strong diel signals that commonly-used synoptic sampling protocols cannot capture (Volkmar et al. 2011). Thus, there is a distinct need to deploy high-frequency, real-time monitoring techniques (e.g., water-quality sondes) to fully assess temporal water-quality patterns after mega-fire perturbations.

Applications to protect municipal-use source waters prominently illustrate the efficacy of real-time monitoring after wildfires (Chow et al. 2021). After wildfires, drinking-water purveyors must address fine sediments, disinfection byproduct (DBP) precursors, and taste, odor, and color issues. To this end, real-time water-quality monitoring can provide an early-warning system to protect source waters. Real-time monitoring of turbidity is readily accomplished as a proxy for fine sediments, which in turn is a proxy for several particle-transported contaminants (e.g., phosphorus, metals, pesticides, PAHs) (Brauer et al. 2009). It is important to note, however, that turbidity is not always highly correlated to suspended sediment where lithology, land use, and soil parameters vary (e.g., Bright and Mager 2020). The use of instream fluorescence or UV probes serves as an excellent tool to quantitatively detect DBP precursors, given their ability to detect aromatic compounds and other DOC constituents. Because many of the taste, odor, and color issues involve DOC constituents, the use of fluorescence/UV sondes provides a relatively simple and inexpensive method to continuously assess source water-quality for drinking water.

At the watershed scale, the deployment of real-time, water-quality sondes at key watershed "integrator" sites can provide important details to assess both the magnitude of water-quality impairment and its subsequent recovery after wildfires, both within burn scars and in downstream regions (Dahm et al. 2015; Ball et al. 2021; Nichols et al. 2024). Because multi-parameter, water-quality sondes and their maintenance require a substantial monetary outlay, it is often infeasible to use this approach to obtain rigorous spatial patterns everywhere. However, the integration of continuous monitoring sondes in conjunction with synoptic sampling can provide a powerful dual approach to assess both spatial and temporal water-quality patterns. For parameters that affect aquatic organism health (e.g., temperature, DO, conductivity), it is the minimum/maximum values that can result in acute organism harm/death. Given large storm-event variability and diel water-quality variability, it is difficult to assess how close these parameters approach the tolerance limits of aquatic organisms (e.g., cold-water fish species) without having a continuous data record. As a sensitive indicator of watershed disturbance and recovery, sediment concentrations/loads are an excellent overall metric. Given that most sediment transport occurs during short time-periods (i.e., storms, rapid snowmelts, rain-on-snow events), it is necessary to deploy real-time turbidity measurements to accurately characterize temporal sediment loads (Thomas 1985; Lewis 1996). However, to achieve accurate results it is necessary to appropriately calibrate the turbidity–sediment relationship with a sufficient number of grab samples.

Finally, for larger streams and reservoirs/lakes, remote-sensing techniques (satellites, unmanned aerial vehicles [UAVs]) can provide a valuable spatial/temporal evaluation of selected water- quality constituents at the surface of the waterbody. Daily satellite passes are available for many locations (but subject to clear sky conditions) with spatial resolutions to the 1- to 30-m scale (Hestir and Dronova 2023). Remote sensing of surface temperature, colored-dissolved organic matter, turbidity, chlorophyll-a (proxy for algal biomass), and cyanobacteria (a proxy for harmful algae species; Bouma–Gregson et al. 2024) has been widely applied. As an example, the Harmful Algal Blooms Analysis Tool (*https://cchab.sfei.org/*) provides a satellite remote-sensing summary of cyanobacteria for the US. To evaluate stream temperature, the use of infra-red (IR) cameras (i.e., thermal imaging temperature sensors) deployed on UAVs allows stream water temperatures to be mapped at high spatial resolutions (30 cm). With the exception of temperature, it is important to note that all these remote-sensing techniques require sufficient calibration with field-collected measurements to assure appropriate data quality. For water-quality parameters that display distinct diel dynamics, it is further necessary to consider the time of day that measurements are available, relative to the minimum/maximum points in the diel signal (Volkmar et al. 2011).

### Trace Elements

Smith et al. (2011) discussed trace elements in their review paper on post-wildfire water quality in streams and rivers in forested catchments. A primary conclusion was that few studies have examined post-fire exports of trace elements. The limited studies of trace elements and post-fire exports that these authors reviewed and discussed found higher levels that exceeded guidelines for iron (Fe), manganese (Mn), arsenic (As), chromium (Cr), aluminum (Al), barium (Ba), and lead (Pb). These high concentrations were associated with highly elevated sediment concentrations. In contrast, the trace elements copper (Cu), zinc (Zn), and mercury (Hg) were below or only slightly above guidelines (Smith et al. 2011). Data on post-fire aquatic concentrations and exports of trace elements were largely unavailable in water-quality studies before 2011, and post-fire measurements of concentrations of trace elements in streams, rivers, and reservoirs were limited. Two conclusions of Smith et al. (2011) concerning trace metals were that further study of post-fire, aquatic ecosystems warrants investigation, and that the duration of elevated trace element concentrations in streams and reservoirs are needed to determine the longevity of post-fire water-quality impairment (White et al. 2006). Further, the chemical speciation of metals strongly affects their potential for toxicity effects. Hence, metal fractionation studies (e.g., particulate, colloidal, organically complexed, free ionic forms) are required to rigorously evaluate the toxicity implications of elevated total metal levels.

Paul et al. (2022) reviewed wildfire-induced changes in receiving waters after large wildfires, focusing on water-quality management. One topic in their review was trace metals that have defined water-quality and drinking-water standards. Of available post-fire studies for comparison, 57% measured increases in metals, 10% measured decreases, and 33% had no change. The duration of positive metal responses was generally less than 5 years (Rust et al. 2018), and metal concentrations increased with a fire's severity (Rust et al. 2019). Catastrophic wildfires mobilize trace elements that are transported by precipitation/runoff events, while recovery occurs in a few years with variable responses in the rates of recovery by different trace elements.

Two recent articles on streams in the western US (Beyene et al. 2023) and southern California (Burton et al. 2016) studied trace elements in stormflow after wildfires. Burton et al. (2016) studied how the 2009 Station Fire (in the Angeles National Forest northeast of Los Angeles) affected trace elements. Suspended sediment was an important transport mechanism for trace elements. Filtered trace element concentrations in post-fire stormwater samples did not exceed standard levels that were greater than criteria for aquatic life, while total concentrations of Fe, Pb, Ni, and Zn were detected at concentrations above established criteria. Beyene et al. (2023) assessed the effects of 54 wildfires in the western US on the trace elements As, Se, and Cd over the first 3 years post-fire. Significant increases in trace element concentrations occurred in streams with large, high-severity mega-fires. Post-fire trace element responses were primarily linked to burn area, burn severity, post-fire weather, surface lithology, catchment physiography, and land cover. Magliozzi et al. (2024) determined that stormwater runoff from the catastrophic Camp Fire, which burned 18,000 structures in Paradise, California, was enriched in major and trace metals in both total concentrations and colloidal concentrations, with many metals exceeding EPA aquatic habitat acute criteria for up to 5 months after the Camp Fire. Trace elements remain an under-studied aspect of post-fire water quality, with multiple variables— such as suspended sediment concentrations, fire characteristics, vegetation type, and rate of vegetation recovery— playing important roles.

The effects of wildfires on mercury (Hg) dynamics are of special importance in the California Coastal Ranges where Hg concentrations are naturally elevated in the bedrock and associated soils (Domagalski et al. 2004). The accumulation of Hg in aquatic sediments has the potential to form highly toxic methyl-Hg, which can bioaccumulate within the aquatic food web of California surface waters, especially the Delta (Marvin–DiPasquale et al. 2009). While many studies have focused on the loss of mercury from burned forests via volatilization during wildfires, few studies have examined the concentrations and reactivity of Hg in the residual ash materials (Engle et al. 2006; Campos et al. 2015; Ku et al. 2018; Li et al. 2022). Hg levels in surficial ash samples from the Wragg and Rocky fires in northern California ranged from 4 to 125 ng/g dry weight (n = 28) (Ku et al. 2018). Ash samples had a significant, but highly variable fraction of Hg in recalcitrant forms (up to 75%), with the percentage of Hg in the recalcitrant pool related to black carbon (i.e., pyrogenic carbon/charcoal) content of the ash. Ash samples were found to strongly sequester aqueous inorganic Hg (up to 0.21 µg $g^{-1}$ ash or 2.2 µg $g^{-1}$ ash-C content) via the formation of complexes between Hg and oxygen-containing functional groups, especially the –COO- group (Li et al. 2022). During anoxic ash incubation with natural surface waters, most ash samples displayed low methylation potential. It was concluded that wildfire ash can sequester Hg into relatively non-bioavailable forms, attenuating the potentially adverse effects of Hg transported with the eroded wildfire ash to downstream aquatic environments (Ku et al. 2018; Li et al. 2022). A study in the Coastal Ranges found that particulate – Hg was the dominant form of riverine-transported Hg after wildfires (Ku et al. 2024). The maximum total suspended solid and total Hg levels in the "first pulse" of a severely burned watershed (100% of watershed burned) were 442 and 46 times higher, respectively, than those at the nearby reference watershed. However, both stream water suspended solid and Hg levels declined substantially in the burned watersheds after just a few rainfall/runoff events.

### Organic Compounds and Contaminants

In their review paper of wildfire effects on water quality in forested catchments, Smith et al. (2011) summarized available information on wildfire and effects on particulate and dissolved organic carbon (POC/DOC), polycyclic aromatic hydrocarbons (PAHs), polychlorinated di-benzo-p-dioxins and dibenzofurans (PCDDs/PCDFs), and polychlorinated biphenyls (PCBs). They concluded that surface dark-colored ash contained a sizeable POC component, and they reported concentrations up to 6.6% POC in ash from high-severity burns from a woodland in California (Goforth et al. 2005). Highly erodible ash did lead to increased exports of POC to streams and rivers. Smith et al. (2011) also found that there is quite limited DOC data from large wildfires. The authors reported that wildfire effects on DOC concentrations in the limited wildfire studies were generally minor. Contaminant studies also were few, with data on PAHs suggesting that sediment and ash samples analyzed for PAHs showed a link to sediment black carbon content (Chen et al. 2022).

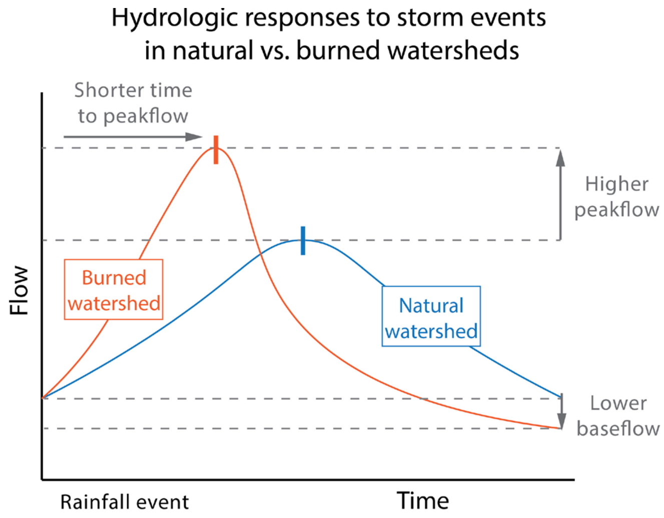


**Figure 3** Conceptual model of stream hydrologic responses to storm events in unburned watersheds compared to recently burned watersheds. Key burned catchment responses for streams are shorter times to peak-flows after rainfall events, higher maximum peak-flows, and lower base-flows in burned catchments. Stream characteristics for unburned catchments are longer times to peak-flows, lower maximum peak-flows, and higher base-flows.

Murphy et al. (2015) sampled DOC from storms after destructive mega-fires in the southwestern US. DOC responded with increased concentrations in stormwater events, especially during the initial precipitation events, post-fire (Figure 3). After the Fourmile Canyon fire in September 2010 in Colorado, Fourmile Creek was sampled above and below the fire scar. Thunderstorms in July of 2011 produced spates that contained peak concentrations of DOC that reached 71 mg $L^{-1}$, with downstream concentrations approximately ten times the DOC concentrations in the upstream sampling sites. A review paper about wildfire-induced water-quality changes by Paul et al. (2022) also reported total organic carbon (TOC) responses after wildfire. Twenty-four studies reported TOC increases, 13 studies reported decreases, and 13 studies reported no change. Because of the role of DOC in disinfection byproduct formation and metal binding, additional studies of DOC responses to large and high-intensity wildfires are much needed.

Chow et al. (2021) addressed the topic of wildfire effects on municipal water supplies in California. Specifically, they considered the characteristics, treatability, and persistence of pyrogenic DOM from burned catchments. Post-fire precipitation leaches organic contaminants, and DOC concentrations depend on fire severity. Burned human infrastructure (from such sources as water pipelines, plastics, electronics, cars, and houses) generate a complex mix of soluble organic contaminants that challenge water-treatment technologies and distribution systems. For example, Odimayomi et al. (2021) reviewed the Camp Fire (Paradise, California) and found chemical contamination of public water-utility-distribution networks, including the presence of various volatile organic carbons (VOCs) and high concentrations of benzene. Hence, water treatability and distribution networks are of critical concern where water supplies are affected by mega-fires of high intensity and in regions where considerable wildland–urban interfaces (WUIs) are present.

Uzun et al. (2020) investigated DOC and organic contaminants for 2 years at two burned California catchments, and compared concentrations to an unburned reference catchment. Concentrations of DOC were significantly higher (67 ± 40%) in the more extensively burned catchment (>90% burned in the Wragg Fire) compared to the reference catchment. Wildfire also elevated concentrations of soluble N-nitrosodimethylamine (NDMA), trihalomethanes (THMs), and haloacetic acids (HAAs), compounds of concern in water treatment. The proportion of catchment burned increased downstream, producing detrimental effects to water quality and impairment scaled to the amount of overall catchment burned (Uzun et al. 2020).

### Nutrients and Primary Producers

Smith et al. (2011) suggested that post-fire stream exports and concentrations of nitrogen (N) and phosphorus (P) result from both atmospheric inputs and runoff inputs from ash, soil erosion, and sediment re-mobilization. Studies up to 2010 did not distinguish whether fluxes of nutrients were derived from ash, soil, or sediment. In addition to natural sources of nutrients, long-term fire retardants are extensively used as a fire-fighting tool, and they contain high concentrations of N and P, which may end up in both terrestrial and aquatic ecosystems (Marshall et al. 2016; Paul et al. 2022). Export data for N and P included multiple nutrient forms such as total P (TP), particulate P (PP), total nitrogen (TN), dissolved organic N (DON), nitrate (NO3-), and ammonia/ammonium (NH3/NH4+). Stream exports of TN and TP in large, burned catchments ranged from 20 to 431 times that of unburned catchments after wildfire, with the highest values the first year after the wildfire. Smith et al. (2011) also noted that (1) longer-term, post-fire nutrient studies are rare, (2) concentrations of dissolved nutrients rarely exceed drinking-water guidelines, and (3) nutrient concentrations of reservoirs after wildfire have not been widely reported.

Oliver et al. (2012) and Uzun et al. (2020) analyzed nutrient responses from the Angora Fire (2007), Wragg Fire (2015), and Rocky Fire (2015) in California. The Angora Fire in the Lake Tahoe basin was the largest and most severe wildfire in the basin, with the potential for nutrient delivery to Lake Tahoe via Angora Creek, a perennial stream that drained the burned catchment (Oliver et al. 2012). Angora Creek was monitored for 2 years after the fire. Nutrient responses included peak stream water concentrations for TN and ammonium within the burned area, and peak concentrations for nitrate, TP, and soluble reactive P below the burned area. TN, nitrate, TP, and total dissolved P all increased in the 2 years after the fire. Uzun et al. (2020) studied the Rocky and Wragg fires (North Coast Range) in comparison to an unburned reference catchment. In the first year after the fires, significantly higher concentrations of DON and ammonium were measured in the burned catchments. Concentrations returned to levels similar to the unburned catchment stream in year two. Nitrate, however, showed a delayed response, with higher values in the burned streams in year two compared to year one. The nutrient increases in the first year were in proportion to the area of catchment burned.

The dynamics of mega-fires on soluble nutrients are generally studied with the use of periodic grab samples. However, Sherson et al. (2015) used continuous water-quality sensors for soluble nitrate and phosphate measurements in the Jemez River of New Mexico in 2011 before, during, and after the catastrophic Las Conchas mega-fire that burned much of the catchment immediately upstream of the river monitoring site. Summer monsoonal precipitation events in 2011 resulted in large multi-day increases in nitrate (six times background levels) and dissolved phosphate (> 100 times background levels). Continuous nutrient monitoring is an emerging technology for studying aquatic ecosystems, and streams and rivers affected by large wildfires are excellent locations to deploy such new sensor technologies (Sherson et al. 2015).

An emerging area of study concerning the effects of large wildfires is the mobilization and transport of small (< 2.5 microns) particles rich in nutrients (Olson et al. 2023). Wildfires mobilize numerous macro- and micro-nutrients, with the largest observed percent increase for phosphorus. A long-term database (2006–2020) in the western US allowed exploration of instances where algal blooms occurred in downwind lakes and reservoirs exposed to elevated nutrients in wildfire smoke. The results suggest a relationship between nutrients from wildfire smoke and the formation of cyanobacteria blooms (Olson et al. 2023).

### Dissolved Oxygen

Smith et al. (2011) did not report or discuss dissolved oxygen (DO) effects in their review paper on water quality in burned forested catchments. However, Verkaik et al. (2013), in a review paper on fire disturbances on streams in Mediterranean climates, mentioned that direct, short-term effects of catastrophic wildfire on streams might include enhanced metabolism contributing to lower stream DO levels. Data from Vila–Escale (2009), presented by Verkaik et al. (2013), showed that 12 days after a large and destructive wildfire in Spain, stream DO concentrations dropped to as low as 0.08 mg $L^{-1}$. About 45 days after the fire (after heavy rains), DO concentrations increased to ~7 mg $L^{-1}$, and anoxic/hypoxic conditions disappeared in the stream water. These data were based on discrete sampling of the streams. Mechanisms—e.g., biological oxygen demand (BOD) or chemical oxygen demand (COD)—for the severe DO sags after the wildfire were not discussed.

Dahm et al. (2015) deployed *in situ* sensors at four sites on the Rio Grande in New Mexico before, during, and after a catastrophic mega-fire (Las Conchas fire) that burned 634 $km^2$ from late June to early August of 2011. Monsoonal thunderstorms, starting in late July and extending through most of August, produced flow pulses off the burn scar that generated multiple DO sags, including five pulses where the river was anoxic or hypoxic (< 2 mg $L^{-1}$) for a few hours at a time. The stronger DO sags propagated downstream in the Rio Grande for over 50 km (Figure 4). Both COD and BOD associated with burn scar material could depress oxygen concentrations, but the exact mechanisms remain elusive. These kinds of extreme water-quality events associated with mega-fires are largely missed, unless networks of continuous DO sensors are deployed within and downstream of the streams and rivers affected by large mega-fires.

Using a network of high-resolution continuous water-quality sensors, Curtis et al. (2025) captured similar DO sags to anoxia in the Klamath River in California in August of 2022 during and after the McKinney mega-fire. A destructive rain-on-fire event on August 2, 2022, created severe water-quality impairments that produced a 95-km fish kill zone downstream of sediment-laden flooding and debris flows. Two severe DO sags at the Seiad Valley gauge station on the Klamath River recorded anoxia for multiple hours on August 3–4. Important questions that urgently need addressing are:

- How widespread are severe DO sags from initial precipitation events immediately after large wildfires?
- How long do these DO sags persist after the wildfire?

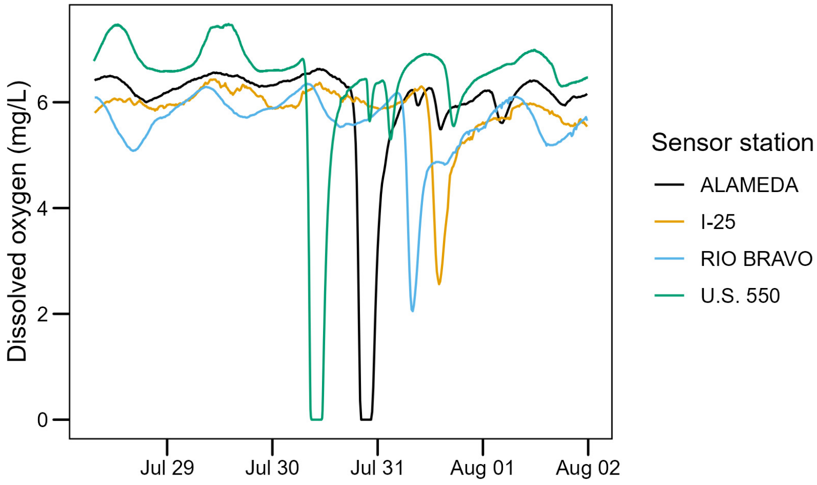


**Figure 4** A dissolved oxygen (DO) sag propagating downstream 50 km in the Rio Grande after a mega-fire in the Jemez Mountains of New Mexico in 2011 where a network of continuous monitoring water quality sensors was deployed. Water-quality responses in streams and rivers shortly after major wildfires can be rapid and severe, requiring continuous data-gathering downstream of the burn scars from mega-fires. *Source: Figure adapted with permission from Dahm et al. (2015).*

- How far downstream do they propagate?
- What are the mechanisms that create these severe sags?

An emerging and valuable assessment tool to evaluate water-quality effects after catastrophic wildfires is the use of high-resolution, temporal data to assess *how long* water quality is affected after wildfires. In addition, these types of data help determine recovery trajectories for streams and rivers after severe wildfires. Costs of deploying and maintaining sensor networks that include multi-parameter probes—including DO probes—are often roadblocks for intensive temporal monitoring, but these data are invaluable for monitoring dynamic and rapidly changing water-quality variables increasingly affected by large and severe mega-fires (Figure 4).

## DISCUSSION TOPICS

### Mega-Fire Effects on Watershed Hydrology

Wildfire effects on water quality are greatly affected by changes in hydrologic flowpaths, which are strongly affected by wildfire severity and the resulting loss of soil cover (e.g., vegetation and forest floor litter; Figures 2 and 3). The persistence of mega-fire effects on water quality is largely dictated by the length of time required for revegetation of the watershed and subsequent formation of a litter layer at the soil surface (Maina and Siirila–Woodburn 2019). In a non-perturbed forest, raindrop impact on the soil is largely attenuated by interactions within the vegetation canopy and the forest litter layer, the latter acting like a sponge to absorb precipitation and slowly release it to the underlying mineral soil. As such, surface runoff, which initiates the soil erosion process, is greatly attenuated in non-perturbed forests (McNabb and Swanson 1990). After a severe fire in which the soil cover is lost to combustion, the bare soil consists of a layer of unconsolidated fine ash that is directly affected by raindrops, inducing soil crusting (surface compaction) that (1) greatly reduces the infiltration rate, (2) promotes surface runoff, (3) increases the concentrations of solutes, and (4) generates soil erosion (Shakesby 2011; Brianne et al. 2020). Thus, during rainstorm events, the peak runoff increases, and the time to peak flow decreases, resulting in accelerated erosion and a higher potential for downstream flooding (Figure 3). In snow-dominated precipitation events, the slow melting of the snowpack largely attenuates surface runoff and erosion, resulting in appreciably less soil erosion. In a warming climate, it is expected that more extreme weather events (e.g., atmospheric rivers) and a greater proportion of rain vs. snow will greatly increase the potential for greater runoff/erosion from severely burned areas (East et al. 2024; East et al. 2025).

Wildfires can further enhance soil runoff and erosion/debris flows by creating hydrophobic layers (i.e., water repellency) within the soil (Debano and Krammes 1966; Debano 2000; Wine and Cadol 2016). At elevated temperatures (> 250 °C), waxy substances in the forest litter (e.g., plant cuticle waxes) are vaporized and transported downward into the cooler soil where the waxes condense, creating a surface/subsurface (0- to 10-cm-depth) hydrophobic wax coating on soil particles. As a result, as rainfall wets the soil after a fire, water penetration into the hydrophobic layer is inhibited, creating soil saturation in the overlying soil layer that can eventually lead to greatly enhanced erosion of the entire surface layer. Once mobilized, these hydrophobicity-driven events can gain progressive downslope momentum that can generate deeper debris flows on steeper slopes. Hydrophobic soil layers gradually break down with wet–dry cycles, freezing–thawing, and animal activity, but may persist for several years. Notably, when surface soil temperatures exceed ~425 °C during intense wildfires, the plant/litter hydrophobic compounds are completely combusted, thereby preventing distinct water-repellent soil layers from forming (Savage 1974; Granged et al. 2011).

Paradoxically, the higher surface runoff during storms events does not diminish base-flow during the dry Mediterranean summers in California (Maina and Siirila–Woodburn 2019). In fact, groundwater recharge and summer river base-flow are generally elevated after severe mega-fires that result in the death of the majority of terrestrial vegetation. The loss of vegetation from watersheds greatly reduces the amount of soil water lost to plant transpiration during the summer growing season (Hornbeck et al. 1993). For example, annual actual ET in the central Sierra Nevada is ~1,350 mm $yr^{-1}$, with the vast majority resulting from plant transpiration (*https://cimas.water.ca.gov*). In the absence of transpiration, the extra water contributes to greater groundwater recharge, and therefore greater river base-flow conditions. The wetter soil conditions also lead to more potential pollutants being from soils (e.g., nitrate), and can lead to lower soil oxygen status, which promotes anaerobic microbial processes such as denitrification and methanogenesis.

The persistence of water-quality impairment by soil erosion and enhanced soil leaching after a severe wildfire largely depends on the dynamics of post-fire vegetation recovery. For example, post-fire vegetation re-establishment after a typical wildfire in the Coastal Ranges of California is very rapid because many fire-adapted species (e.g., chaparral species) re-sprout from their rooting system, and annual grasses/forbs proliferate from the large seed banks in the soil (Uzun et al. 2020). As a result, soil cover rapidly recovers (largely within 2 years) as fall rains naturally induce the germination of annual species. However, annual species typically do not experience accelerated growth to generate soil cover until about March/April, when the higher solar radiation and temperature stimulate their rapid growth (Larsen et al. 2021). Thus, there is a critical window between the initiation of fall/winter rainfall and about March, when burned landscapes remain especially susceptible to runoff/erosion. In contrast, severe wildfires in the coniferous forests of the Sierra Nevada may take decades to regenerate sufficiently to the point of providing adequate soil cover to reduce soil runoff/erosion. Vegetation establishment/plant uptake is also a critical factor that regulates nutrients being leached from post-fire soils. The intact rooting system of stump-sprouting vegetation in the Coastal Ranges continues to extract nutrients from the soil, whereas the death of the rooting system in burned coniferous forests prevents nutrient uptake, hence thus leading to increased nutrient leaching (Dahlgren 1998).

The post-fire death of roots in coniferous forests also leads to the potential for mass wasting events (e.g., soil slumping, landslides) on steeper hillslopes. By acting as a reinforcement agent, rooting systems provide critical structural stability for hillslopes. As the dead roots decay, but before new rooting systems re-establish, there is often a period between about 6 to 15 years post-fire, when the overall rooting system provides little reinforcement to hillslopes (Dahlgren et al. 2001; Phillips et al. 2015; Figure 5). This is a period

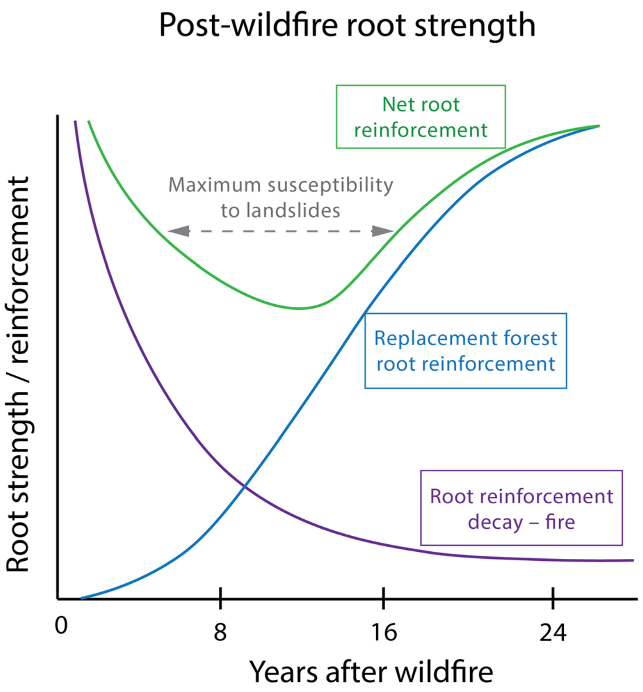


**Figure 5** Conceptual model of the role of tree roots in the susceptibility of watersheds to landslides. Post-wildfire there is decay in root reinforcement that is impacted by whether there is vegetative re-sprouting from the burned trees and by the rate of forest replacement post-wildfire. There is a period of time about 1 to 2 decades after mega-fires when susceptibility to landslides is at a peak, and downstream water quality degradation can occur. *Source: Diagram after Phillips et al. (2015).*

of time when mass wasting events increase, with the potential to greatly impair downstream water quality and aquatic habitat.

### Implications for Stream Aquatic Habitats

Wildfires can strongly affect riparian ecosystems and associated stream aquatic habitat (Bixby et al. 2015; Jager et al. 2021; Lawrence et al. 2022; Erdozain et al. 2024). In the semi-arid forests/shrublands of California, the riparian zone often acts as a corridor for wildfire transmission as they accumulate large fuel loads because of enhanced productivity fueled by the availability of groundwater (North 2012). An immediate effect of removing the riparian canopy is that the temperature of streams can increase notably because increased solar radiation can reach the stream channel. As an analog to severe wildfire, timber harvests in northern California lead to an approximately 2 °C increase in stream temperatures at sites with the most intensive harvesting treatment (Miralha et al. 2024). Increased temperature will be more prominent in low-flow headwater streams where maximum daily temperatures may exceed the reported lethal limits for trout, such as > 25 °C for rainbow trout (Matthews and Berg 1997). Moreover, higher water temperatures, especially at higher elevations, will greatly reduce the dissolved oxygen saturation levels and may contribute to hypoxic conditions. For example, dissolved oxygen saturation levels for freshwaters at sea level and 20/30 °C are 9.09/7.56 mg $L^{-1}$ vs. 7.19/5.95 mg $L^{-1}$ at 2,000 m (*https://water.usgs.gov/cgi-bin/dotables*). However, increased summer baseflow that results from decreased watershed ET because of the loss of vegetation may counteract the temperature increase to some extent by providing larger inputs of cooler groundwater.

Increased solar radiation on the stream channel increases primary productivity, and may change the base of the instream food web to a dominance by autochthonous vs. allochthonous carbon sources. Instream primary production may be further enhanced by increased mineral N ($NH_4$, $NO_3$) and P ($PO_4$) concentrations. These changes in temperature and organic substrates may significantly affect the entire aquatic food web (Oliver et al. 2012; Jager et al. 2021). Riparian plant species often regenerate relatively quickly because of their stump-sprouting characteristics, increased mineral nutrient concentrations, high plant available water, and full sunlight. Hence, post-fire riparian zone recovery will tend to occur much faster than recovery in the surrounding upland forest.

In addition to decreased canopy coverage, stream bank stability declines and substrate characteristics (fine sediments vs. gravels vs. cobbles) may change along the longitudinal stream channel (Oliver et al. 2012). In headwater portions of the catchment (i.e., steeper stream gradient), increased surface runoff/erosion during storms events may scour fine sediments and expose cobbles within the stream channel. With a decrease in the downstream gradient, fine sediments may be deposited, resulting in the burial of gravel/cobble substrates, which are important for fish spawning habitat (Louhi et al. 2011). In response to changes in stream temperature, solar radiation, nutrient availability and substrate quality, the benthic macroinvertebrate communities may change appreciably (Oliver et al. 2012). The more severe the mega-fire, the more severely the instream habitat is adversely affected. In the longer term, standing dead trees may fall across the stream channel to become large, woody debris dams that create pool/riffle habitats, which will vastly alter aquatic habitat conditions, perhaps in several beneficial ways. To improve our understanding of how wildfires potentially affect aquatic habitats, future studies are strongly warranted that address long-term, longitudinal stream habitat impairment, and recovery from wildfires of contrasting severity (Power et al. 2024).

### Implications for Reservoirs

A major water-quality effect of mega-fires is increased runoff/erosion that results in sediments (both organic and inorganic) being transported to downstream lakes and reservoirs. This transport of sediments to downstream reservoirs will ultimately decrease the water-storage capacity of reservoirs. For example, Dow et al. (2024) found that 57% of statewide post-fire sediment erosion occurred upstream of reservoirs, with an increasing prominence in recent decades for northern California. Based on historic rates of sediment accumulation in California reservoirs, sediment accumulation is predicted to reach 7.1 billion $m^3$ by 2200 (15% of statewide total reservoir storage capacity) (Minear and Kondolf 2009). Increased sediment deposition in reservoirs because of severe and extensive wildfires could greatly increase reservoir sedimentation as compared to historic rates. The erosion response to wildfires will be strongly affected by geologic/soil properties, with generally higher erosion rates in regions with sedimentary rocks (Coastal Ranges) vs. igneous rocks (Sierra Nevada). Coupled with climate- change projections for more extreme weather events and more precipitation in the form of rainfall, the storage capacity of reservoirs plays a key role in flood mitigation and water availability for municipal/agriculture use during the summer dry season.

In addition to decreasing reservoir storage capacity, increased inputs of fine sediment may temporarily reduce the depth of the photic zone, thereby affecting primary productivity in reservoirs—and potentially the Delta. Sediments that contain elevated concentrations of organic matter will substantially increase biological and sediment oxygen demand (BOD/SOD), which may cause hypoxic/anoxic conditions in bottom waters and sediments, with an associated potential for Hg methylation and release of metals from sediments. For instance, elevated inputs of Hg bound to aromatic components of pyrolyzed organic matter in particulate matter from runoff/erosion were demonstrated in the first year after wildfires in Hg-rich watersheds of California's Coastal Range (Li et al. 2022; Ku et al. 2018). Because many of California's reservoirs contain legacy Hg from Hg mining (Coastal Ranges) and gold mining (Sierra Nevada), further inputs of Hg coupled with more persistent anoxic conditions could substantially increase methyl-Hg concentrations within reservoirs, as well as within downstream waterways (e.g., the Delta).

Increased nutrient loads (N/P) may stimulate lake/reservoir eutrophication in the absence of light limitation from suspended sediments, including the propagation of harmful algal blooms (HABs). Reoccurring and persistent HABs in the Delta (monitored through the CA HABS Network, available from: *https://mywaterquality.ca.gov/habs/*) and from publications by Preece et al. 2024) and Smith et al. (2023) highlight areas that are susceptible to increased nutrient inputs from wildfires. The longer water residence times in lakes/reservoirs vs. rivers/streams allow algal communities a greater time to assimilate nutrients, leading to much higher algal concentrations than in river/stream ecosystems. The longer residence times also allow more time for microbial mineralization of organic substrates in the hypolimnion and sediments, resulting in the export of mineralized nutrient forms (e.g., $NH_4$, $NO_3$, $PO_4$) rather than organically bound nutrients in reservoir releases from the hypolimnion (Ahearn et al. 2005). Overall, low-order riverine systems (headwater streams) can recover relatively quickly from water-quality impairments as they are continuously flushed by streamflow. In contrast, reservoirs accumulate pollutants from upstream and provide a greater water residence time for biological activity to interact with pollutants (e.g., eutrophication/Hg-methylation). Thus, for several years post-mega-fire, adverse effects on lakes/reservoirs may persist because of the internal recycling (between sediment and water column) that occurs in large lake/reservoir ecosystems (Smith et al. 2023).

### Wildfire-Water-Quality Projections in a Warming Climate

Climate-change effects on North Coastal rivers and Sierra Nevada mountains will have the greatest effects on California’s freshwater surface resources because they currently serve as primary water sources for California (Lund 2016). Compared to the baseline period of 1976–2005, the end-of-century temperature increases for California are projected to be +1.6°C and +5°C respectively for the Paris Agreement +2°C and RCP 8.5 (current emissions) scenarios (California’s Fourth Climate Change Assessment 2018). These projected temperature increases will result in a substantially decreased April 1st winter snowpack (–74% for the RCP 8.5 scenario) and soil moisture status (–10% for the RCP 8.5 scenario). Compared to the baseline period (1976–2005), wildfire area is projected to increase by 63% and 20% for the RCP 8.5 and Paris Agreement 2°C scenarios, respectively (Franco et al. 2018; Westerling 2018). Large-acreage mega-fires are expected to comprise a larger fraction of the total burned area, which is of great concern because they may delay or permanently alter forest vegetation recovery, and may convert some forest ecosystems to shrubland or grassland communities (Stephens et al. 2014). High-elevation forests may be disproportionately affected because the fire-regime in these ecosystems is currently climate-limited, as opposed to lower-elevation forests that are primarily fuel-limited (Steel et al. 2015). Fuel-limited forests have climate conditions that allow for fires each year if fuels are available. In contrast, climate-limited forests generally have sufficient fuel accumulations to support wildfires but will only burn in years when the system substantially dries, such as in drought years under current climate fluctuations. Because climate warming will decrease soil moisture, summer relative humidity, and snowpack duration, the summer–fall period will be much drier in these high-elevation ecosystems, potentially converting them to a fuel-limited system. Thus, high-elevation forests are likely to become more susceptible to greater wildfire effects, relative to current conditions, both in terms of the extent of mega-fires and burn intensity.

In addition to overall climate warming, extreme weather events are likely to play a disproportionate role in wildfire–water-quality interactions (Murphy et al. 2023). California’s future climate is expected to experience both more frequent extreme droughts and wet periods (e.g., larger atmospheric rivers). Droughts significantly affect the health of forests because extreme moisture stress weakens the forest’s response to insect and disease attack (Cheng et al. 2024). The death of trees substantially increases dry fuel load, especially in closed-canopy forests, which will lead to more intense mega-fires. Periods of drought also lead to more fires, which leads to more overall burned acreage. Hence, severe drought conditions will likely lead to larger and more intensively burned acreages. Extreme precipitation events in a warmer California will lead to greater winter rainfall vs. snowfall and rain-on-snow events that generate high surface runoff/erosion over burned areas, causing potentially severe water-quality impairment (Rhoades et al. 2018). Additionally, an increased prevalence of strong wind events (e.g., Santa Ana and Diablo winds) can create catastrophic wildfires that cover large acreages (Murphy and Mass 2025). A northward extension of the southwestern US summer monsoon pattern may also contribute to greater thunderstorm activity, which could greatly increase fire ignition from lightning strikes (Young et al. 2017). Hence, extreme weather events (e.g., extreme droughts, heavy precipitation, strong intense winds, and lightning strikes) are likely to affect future surface water quality.

Most notable, the projected increase in more intense and larger fires, especially at higher elevations, presents the greatest water-quality impairment concerns from wildfires. As previously discussed, the greater the percentage of the watershed area burned (linear effect) and the greater the intensity of the fire (exponential effect), the greater the potential for water-quality degradation. Therefore, to protect critical water resources, forest practices that limit the size and intensity of wildfires are required. The greatest impairments to water quality after wildfires tend to occur in the first few storms after the dry season (Dahm et al. 2015; Reale et al. 2015; Uzun et al. 2020). Post-fire soil-management treatments (e.g., surface applications of straw, grass seeding, straw waddles, log erosion barriers) have little ability to effectively treat large and intensively burned watersheds, even when applied to hydrologically sensitive areas. Thus, water purveyors might consider developing alternate water sources (e.g., small reservoirs, groundwater wells) that could be used to avoid water intake during the first-flush runoff events after severe mega-fires that consume a large portion of their source-water watershed (Chow et al. 2021).

## KEY POINTS AND SUMMARY THOUGHTS

A two-panel conceptual figure shows a suite of activities that accompany a mega-fire and short-term postfire responses to devastation and destruction from large and often high-intensity wildfire (Figure 6). The left-side panel of Figure 6 represents some of the fire-fighting activities used to combat mega-fires where they arise. Mega-fires present many immediate challenges to fire-fighters; particularly critical short-term goals are safeguarding human life, protecting human infrastructure, and maintaining fire-fighter safety. Tools such as retardant drops, introduced backfires, water drops, heavy-equipment deployment, and emergency supplies are often needed to bring mega-fires under control. Satellite and aircraft remote-sensing allows assessment of (1) the size and location of mega-fire activity, (2) the location of hot spots for special attention, and (3) localized weather conditions to guide fire-fighting activities.

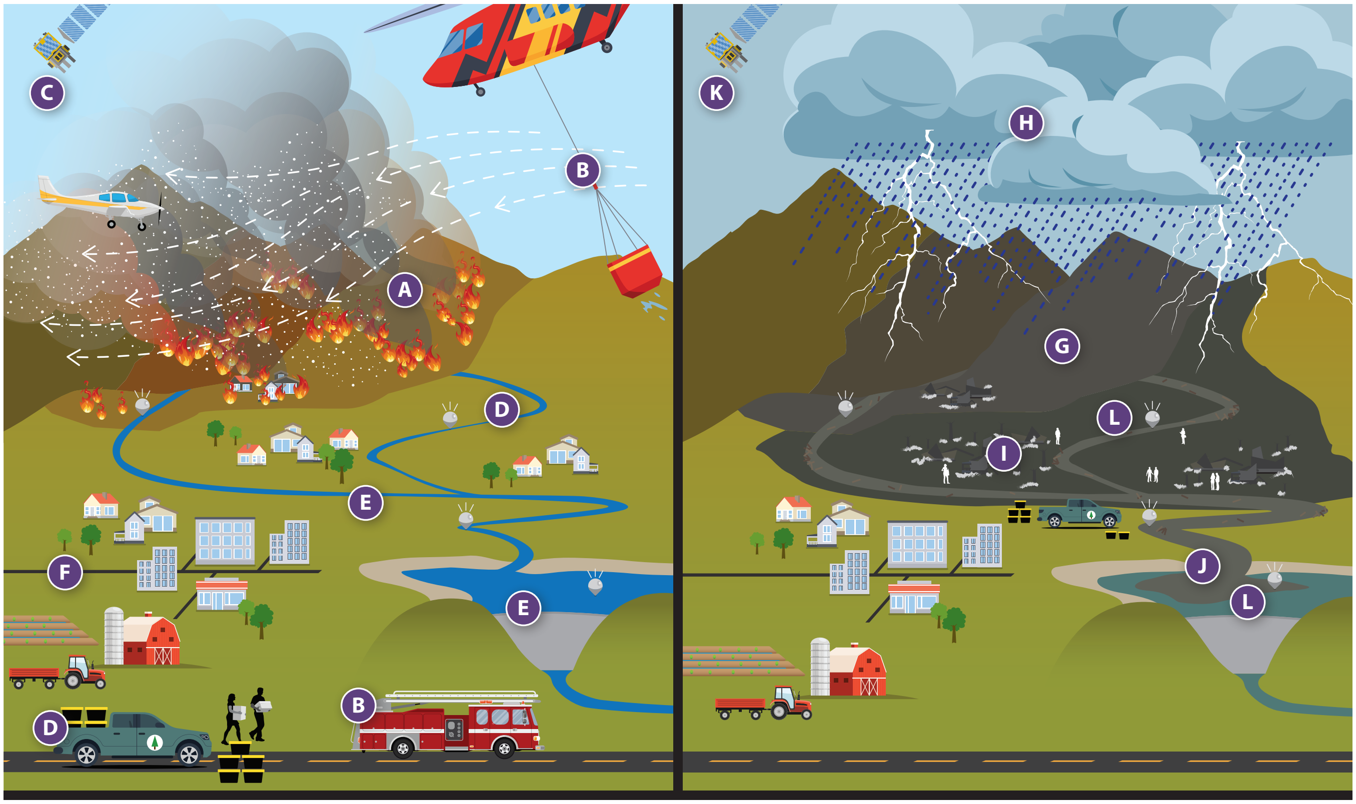
The right-side panel of Figure 6 depicts major dangers that mega-fires burn scars produce on the landscape, especially from heavy rainfalls that occur shortly after mega-fire have been suppressed. The burned landscape is susceptible to producing water-quality-degrading events that propagate downstream. The wildland-urban interface (WUI) is a hot spot for the mobilization and transport of organic contaminants and heavy metals. Many contaminants propagate downstream to reservoirs where longer residence times are common. Airborne remote- sensing helps track the mobilization and movement of water-quality-degrading compounds, and in situ continuous monitoring captures rapid and short-term sags or pulses of low DO, turbidity, conductivity, pH, metals, organic compounds, and nutrients. Mega-fires continue to degrade water quality for months to years after active wildfire.

The main focus for this paper is on how large and high intensity mega-fires affect water quality in the catchment of the Sacramento–San Joaquin Delta. Some key points on the ways mega-fires can affect catchments that drain into the Delta include the following:

- Wildfires are inevitable in arid and semi-arid wildlands worldwide, including the California Delta watershed; concurrently, global climate change is adversely affecting wildfire dynamics at global scales, with a clear and strong response of larger and more intense wildfires in California.

- The eight largest wildfires in California since 1932 have all occurred from 2018 to 2024, and the burn scars from these wildfires are all at least partially within the Delta watershed (Figure 1). The area burned by these eight wildfires total 1.18 million hectares (~3% of California's total land area).

- Reducing the intensity and size of wildfires is key to protecting the quality of water resources in California, but in a rapidly changing climate (e.g., warmer, and drier conditions) the recovery of forest ecosystems from wildfire in California is becoming progressively more difficult.



**A.** Active fire zone with extreme winds
**B.** Fire fighting efforts
**C.** Remote sensing monitoring
**D.** In situ monitoring

**E.** Vulnerable downstream aquatic ecosystems
**F.** Infrastructure protection
**G.** Post-fire burn scar
**H.** Active thunderstorm

**I.** Burned wildland urban interface (WUI)
**J.** Downstream water quality effects
**K.** Post-fire remote sensing monitoring
**L.** Post-fire in situ monitoring

**Figure 6** This two-panel conceptual figure shows an active mega-fire and the resultant burn scar and water-quality effects. The *left side* of the figure shows active fire-fighting efforts to save lives and property, remote sensing for monitoring the extent and severity of the wildfire, and downstream infrastructure potentially about to be affected by the fire. The *right side* of the figure shows the resultant devastation of the mega-fire, with atmospheric events that transport water-quality contaminants within the burn scar and to waterbodies downstream. Mega-fire size and intensity, wildland urban interfaces (WUIs), forest recovery rates, and aqueous sensor deployment and monitoring are immediate post-fire activities to assess water-quality effects from larger and more intense wildfires in catchments of the California Delta.

- The recovery of water quality from wildfire is largely a function of the speed of vegetative regrowth. Water-quality impairments generally respond linearly with the percentage of the watershed area burned, and exponentially as burn severity increases.

- Urban areas and WUIs are hot spots for organic contaminants and heavy metals that impair water resources and affect water treatment. Many of these contaminants are transported downstream in solution or attached to sediment particles.

- Forest (wildland) management can help reduce potential threats to humans, infrastructure, and nature. Traditional ecological knowledge of fuel management plays a crucial role in future forest management (Hankins 2024), and in a rapidly changing climate historic and current contributions from Indigenous peoples could help guide forest and fire management.

These following summary thoughts, drawn from themes in this manuscript, are designed to help identify future research and monitoring needs in large watersheds like the Delta that are increasingly impaired by a hotter climate and more combustible fuel loads.

- Atmospheric deposition of small particles linked to smoke from wildfires is an important topic for future research in the Delta watershed, because they affect both humans and ecosystems. Human-health effects and effects on sensitive high-elevation lakes and reservoirs deserve special attention.

- Severe water-quality impairment is commonly linked to strong precipitation events that generate spates and debris avalanches that occur soon after the wildfire has ended (Figure 6).

- Continuous in situ measurements enhance documentation of the severity and duration of episodic pulses of flow on water quality (Figure 4). Highly responsive water-quality parameters amenable to continuous monitoring methods are dissolved oxygen (DO), turbidity, conductivity, pH, temperature, DOC, chlorophyll, and some dissolved nutrients.

- Measurements of initial stormflows after mega-fires have recently deployed *in situ* DO probes that continuously measure DO concentrations. Strong DO sags, sometimes to anoxia, have been documented. More of these types of studies are crucial to understand water quality and biological responses after mega-fires in California.

- Few studies have examined post-mega-fire exports of trace element concentrations and forms from forested catchments. The duration and pattern of elevated trace element concentrations in streams, rivers, and reservoirs is needed to determine the longevity of post-mega-fire water-quality impairment (Figure 2).

- Until quite recently, dissolved organic carbon (DOC) was rarely measured in streams and rivers affected by mega-fires. Limited data led to the conclusion that DOC effects from large wildfires were minor, but recent studies conclude that, in initial storm events after major wildfires, DOC increases. There is still much to learn about DOC dynamics and their effects on the formation of disinfection byproducts during water treatment.

- Reservoirs appear to play a key role in ameliorating downstream water-quality effects after catastrophic wildfire, but rigorous reservoir studies are currently limited in California and worldwide.

Mega-fires are extreme events that are increasing in both size and intensity throughout California. The Delta watershed has experienced numerous mega-fires in the past few years, and more are inevitable. This manuscript presents some of the main water-quality effects from large high-intensity wildfires, and suggests research and monitoring needs to reduce and respond to water-resource management challenges in a changing world.

## ACKNOWLEDGEMENTS

We thank Vincent Pascual (Office of State Publishing) for his help in preparing Figures 2 and 6. We also thank Megan Thomson (Delta Stewardship Council) for preparing the map of the Delta catchment, including the eight largest mega-fires since 2018 with fire locations, areal extent, and severity. We thank Justin Reale of the United States Geological Survey (USGS) for the data demonstrating the strong dissolved oxygen sags after the Las Conchas mega-fire in New Mexico (Figure 4). We also thank Janet K Thompson (USGS retired), Maggie Christman (Delta Science Program), and Lisamarie Windham–Myers (Delta Stewardship Council Lead Scientist) for reviewing earlier drafts of this paper. Finally, we thank Hwaseong Jin and an anonymous reviewer, whose feedback very much improved the manuscript.

## REFERENCES

Ahearn DS, Sheibley RW, Dahlgren RA. 2005. Effects of river regulation on water quality in the lower Mokelumne River, California. River Res Appl. [accessed 2025 Jul 3];21:651–670. *https://doi.org/10.1002/rra.853*

Alshehri T, Wang J, Singerling SA, Gigault J, Webster JP, Matiasek SJ, Alpers CN, Baalousha M. 2023. Wildland–urban interface fire ashes as a major source of incidental nanomaterials. J Haz Mater. [accessed 2025 Jul 3];443, part B:1330311. *https://doi.org/10.1016/j.jhazmat.2022.130311*

Ball G, Regier P, Gonzalez–Pinzon R, Reale J, Van Horn D. 2021. Wildfires increasingly impact western US fluvial networks. Nat Commun. [accessed 2025 Jul 3];12:2484. *https://doi.org/10.1038/s41467-021-22747-3*

Beyene MT, Leibowitz SG, Dunn CJ, Bladon KD. 2023. To burn or not to burn: an empirical assessment of the effects of wildfires and prescribed fires on trace element concentrations in Western US streams. Sci Total Environ. [accessed 2025 Jul 3];863:160731. *https://doi.org/10.1016/j.scitotenv.2022.160731*

Bixby RJ, Cooper SD, Gresswell RE, Brown LE, Dahm CN, Dwire KA. 2015. Fire effects on aquatic ecosystems: an assessment of the current state of the science. Freshw Sci. [accessed 2025 Jul 3];34(4):1340–1350. *https://doi.org/10.1086/684073*

Bouma–Gregson K, Bosworth D, Flynn TM, Maguire A, Rinde J, Hartman R. 2024. Delta blue(green)s: the effect of drought and drought-management actions on *Microcystis* in the Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci. [accessed 2025 Jul 3];22(1). *https://doi.org/10.15447/sfews.2024v22iss1art2*

Bowman MJS, Sharples JJ. 2023. Taming the flame, from local to global extreme wildfires. Science. [accessed 2025 Jul 3];381:616–619. *https://doi.org/10.1126/science.adi8066*

Brauer N, O'Geen AT, Dahlgren RA. 2009. Temporal variability in water quality of agricultural tailwaters: implications for water quality monitoring. Agricult Water Manag. [accessed 2025 Jul 3];96:1001–1009. *https://doi:10.1016/j.agwat.2009.01.011*

Brianne P, Hernandez R, Lipson D. 2020. The fate of biological soil crusts after fire: a meta-analysis. Glob Ecol Conserv. [accessed 2025 Jul 3];24:e01380. *https://doi.org/10.1016/j.gecco.2020.e01380*

Bright CE, Mager SM. 2020. A national-scale study of spatial variability in the relationship between turbidity and suspended sediment concentration and sediment properties. River Res Appl. [accessed 2025 Jul 3];36:1449–1459. *https://doi.org/10.1002/rra.3679*

Burton CA, Hoefen TM, Plumlee GS, Baumberger KL, Backlin AR, Gallegos E, Fisher RN. 2016. Trace elements in stormflow, ash, and burned soil following the 2009 Station Fire in Southern California. PLOS ONE. [accessed 2025 Jul 3];11(5): e0153372. *https://doi.org/10.1371/journal.pone.0153372*

California's Fourth Climate Change Assessment. 2018. California Natural Resources Agency Publication Number: CCCA4-CNRA-2018-009; Green Nylen G, Kiparsky M, Owen D, Doremus H, Hanemann M. [accessed 2025 Aug 20].

Campbell PC, Tong D, Saylor R, Li Y, Ma Siqi, Zhang X, Kondragunta S, Li F. 2022. Pronounced increases in nitrogen emissions and deposition because of the historic 2020 wildfires in the western US. Sci Total Environ. [accessed 2025 Jul 3];839:156130. *https://doi.org/10.1016/j.scitotenv.2022.156130*

Campos I, Vale C, Abrantes N, Keizer JJ, Pereira P. 2015. Effects of wildfire on mercury mobilisation in eucalypt and pine forests. Catena. [accessed 2025 Jul 3];131:149–159. *https://doi.org/10.1016/j.catena.2015.02.024*

Chen H, Wang J–J, Ku P–J, Tsui MT–K, Abney RB, Berhe AA, Zhang Q, Burton SD, Dahlgren RA, Chow AT. 2022. Burn intensity drives the alteration of phenolic lignin to (poly) aromatic hydrocarbons as revealed by pyrolysis gas chromatography-mass spectrometry (Py-GC/MS). Environ Sci Technol. [accessed 2025 Jul 3];56(17):12678–12687. *https://doi.org/10.1021/acs.est.2c00426*

Cheng Y, Oehmcke S, Brandt M, Rosenthal L, Das A, Vrieling A, Saatchi S, Wagner F, Mugabowindekwe M, Verbruggen W, et al. 2024. Scattered tree death contributes to substantial forest loss in California. Nat Commun. [accessed 2025 Jul 3];15:641. *https://doi.org/10.1038/s41467-024-44991-z*

Chow AT–S, Karanfil T, Dahlgren RA. 2021. Wildfires are threatening municipal water supplies. Eos. [accessed 2025 Jul 4];102. *https://doi.org/10.1029/2021EO161894*

Curtis JA, Johnson G, Cahill J, Ray K, Genzoli L, Dahm CN, Schenk L. 2025. 2022 McKinney rain on wildfire event, dissolved oxygen sags, and a fish kill on the Klamath River, California. Nat Sci Rep. [accessed 2025 Aug 20];15(July 2025):24668. *https://doi.org/10.1038/s41598-025-08179-9*

Dahlgren RA. 1998. Effects of forest harvest on stream water quality and nitrogen cycling in the Caspar Creek watershed. In: Conference on Coastal Watersheds - The Caspar Creek Story. Gen. Tech. Rep. PSW-126. Berkeley (CA): USDA, PSW Forest and Range Experiment Station. p. 45–53. Available from: *https://www.fs.usda.gov/psw/publications/documents/psw_gtr168/06dahlgren.pdf*

Dahlgren RA, Driscoll CT. 1994. The effects of whole-tree clear-cutting on soil processes in the Hubbard Brook Experimental Forest, New Hampshire, USA. Plant Soil. [accessed 2015 Jul 3];158:239–262. *https://doi.org/10.1007/BF00009499*

Dahlgren RA, Tate KW, Ahearn DS. 2005. Watershed scale, water quality monitoring–water sample collection. In: Down RD, Lehr JH, editors. Environmental instrumentation and analysis handbook. San Francisco (CA): John Wiley and Sons. 1,080 p. Available from: *https://www.wiley.com/en-us/Environmental+Instrumentation +and+Analysis+Handbook-p-9780471463542*

Dahm CN, Candelaria–Ley RI, Reale CS, Reale JK, Van Horn DJ. 2015. Extreme water quality degradation following a catastrophic forest fire. Freshw Biol. [accessed 2025 Jul 4];60:2584–2599. Available from: *https://postfiresw.info/sites/default/files/Dahm_2015.pdf*

DeBano LF. 2000. The role of fire and soil heating on water repellency in wildland environments: a review. J Hydrol. [accessed 2025 Jul 4];231:195–206. *https://doi.org/10.1016/S0022-1694(00)00194-3*

DeBano LF, Krammes JS. 1966. Water repellent soils and their relation to wildfire temperatures. Hydrol Sci J. [accessed 2025 Jul 4];11(2):14–19. *https://doi.org/10.1080/02626666609493457*

Dennison PE, Brewer SC, Arnold JD, Moritz MA. 2014. Large wildfire trends in the western United States, 1984–2011. Geophys Res Lett. [accessed 2025 Jul 4];41:2928–2933. *https://doi.org/10.1002/2014GL059576*

Dettinger MD, Ralph FM, Das T, Neiman PJ, Cayan DR. 2011. Atmospheric rivers, floods and the water resources in California. Water. [accessed 2025 Jul 4];3:445–478. *https://doi.org/10.3390/w3020445*

Domagalski JL, Alpers CN, Slotton DG, Suchanek TH, Ayers SM. 2004. Mercury and methylmercury concentrations and loads in the Cache Creek watershed, California. Sci Total Environ. [accessed 2025 Jul 4];327:215–237. *https://doi.org/10.1016/j.scitotenv.2004.01.013*

Dove NC, Tas N, Hart SC. 2022. Ecological and genomic responses of soil microbiomes to high-severity wildfire: linking community assembly to functional potential. ISME J. [accessed 2025 Jul 4];16:1853–1863. *https://doi.org/10.1038/s41396-022-01232-9*

Dow HW, East AE, Sankey JB, Warrick JA, Kostelnik J, Lindsay DN, Kean JW. 2024. Postfire sediment mobilization and its downstream implications across California, 1984–2021. J Geophy Res—Earth Surface. [accessed 2025 Jul 4];129:e2024JF007725. *https://doi.org/10.1029/2024JF007725*

East AE, Logan JB, Dartnell P, Dow HW, Lindsay DN, Cavagnaro DB. 2025. Post-fire sediment yield from a western Sierra Nevada watershed burned by the 2021 Caldor Fire. Earth Space Sci. [accessed 2025 Jul 4];12:e2024EA003939. *https://doi.org/10.1029/2024EA003939*

East AE, Logan JB, Dow HW, Smith DP, Iampietro P, Warrick JA, Lorenson TD, Hallas L, Kozlowicz B. 2024. Post-fire sediment yield from a central California watershed: field measurements and validation of the WEPP model. Earth Space Sci. [accessed 2025 Jul 4];11:e2024EA003575. *https://doi.org/10.1029/2024EA003575*

Elliott SM, Hornberger MI, Rosenberry DO, Frus RJ, Webb RM. 2024. A conceptual framework to assess post-wildfire water quality: state of the science and knowledge gaps, Wat Resour Res. [accessed 2025 Jul 4];60:e2023WR036260. *https://doi.org/10.1029/2023WR036260*

Engle MA, Gustin MS, Johnson DW, Murphy JF, Miller WW, Walker RF, Wright J, Markee M. 2006. Mercury distribution in two Sierran forests and one desert sagebrush steppe ecosystems and the effects of fire. Sci Total Environ. [accessed 2025 Jul 4];367:222–233. *https://doi.org/10.1016/j.scitotenv.2005.11.025*

Erdozain M, Cardill A, de–Miguel S. 2024. Fire effects on the biology of stream ecosystems: a synthesis of current knowledge to guide future research and integrated fire management. Glob Chang Biol. [accessed 2025 Jul 4];30:e17389. *https://doi.org/10.1111/gcb.17389*

Farruggia MJ, Brahney J, Tanentzap AJ, Brentrup JA, Brighenti LS, Chandra S, Cortes A, Fernandez RC, Fischer JM, Forrest AL, et al. 2024. Wildfire smoke effects lake ecosystems. Glob Chang Biol. [accessed 2025 Jul 4];30:e17367. *https://doi.org/10.1111/gcb.17367*

Franco B, Clarisse L, Stavrakou T, Muller J–F, Van Damme M, Whitburn S, Hadji–Lazaro J, Hurtmans D, Taraborrelli D, Clerbaux C, et al. 2018. A general framework for global retrievals of trace gases from IASI: application to methanol, formic acid, and PAN. J Geophys Res—Atmospheres. [accessed 2025 Jul 4];123:13,963–13,984. *https://doi.org/10.1029/2018JD029633*

Goforth BR, Graham RC, Hubbert KR, Zanner CW, Minnich RA. 2005. Spatial distribution and properties of ash and thermally altered soils after high-severity forest fire, southern California. Intl J Wildland Fire. [accessed 2025 Jul 4];14:343–354. Available from: *https://research.fs.usda.gov/treesearch/43410*

Granged AJP, Zavala LM, Jordan A, Bárcenas–Moreno G. 2011. Post-fire evolution of soil properties and vegetation cover in a Mediterranean heathland after experimental burning: a 3-year study. Geoderma. [accessed 2025 Jul 4];164(1–2):85–94. *https://doi.org/10.1016/j.geoderma.2011.05.017*

Hankins DL. 2024. Climate resilience through ecocultural stewardship. Proc Nat Acad Sci. [accessed 2025 Jul 4];121(32):e2310072121. *https://doi.org/10.1073/pnas.2310072121*

Hestir E, Dronova I. 2023. Remote sensing of primary producers in the Bay–Delta. San Franc Estuary Watershed Sci. [accessed 2025 Jul 6];20(4). *https://doi.org/10.15447/sfews.2023v20iss4art5*

Hornbeck JW, Adams MB, Corbett ES, Verry ES, Lynch JA. 1993. Long-term effects of forest treatment on water yield: a summary for northeastern USA. J Hydrol. [accessed 2025 Jul 6];150:323–344. *https://doi.org/10.1016/0022-1694(93)90115-P*

Jager HI, Long JW, Malison RL, Murphy BP, Rust A, Silva LGM, Sollmann R, Steel ZL, Bowen MD, Dunham JB, et al. 2021. Resilience of terrestrial and aquatic fauna to historical and future wildfire regimes in western North America. Ecol Evol. [accessed 2025 Jul 6];11(18):12259–12284. *https://doi.org/10.1002/ece3.8026*

Keeley JE, Syphard AD. 2021. Large California wildfires: 2020 fires in historical context. Fire Ecol. [accessed 2025 Jul 6];17(22). *https://doi.org/10.1186/s42408-021-00110-7*

Koplitz SN, Nolte CG, Sabo RD, Clark CM, Horn KJ, Thomas RQ, Newcomer–Johnson TA. 2021. The contribution of wildland fire emissions to deposition in the US: implications for tree growth and survival in the Northwest. Environ Res Lett. [accessed 2025 Jul 6]16:024028. *https://doi.org/10.1088/1748-9326/abd26e*

Ku P, Tsui MT–K, Nie X, Chen H, Hoang TC, Blum JD, Dahlgren RA, Chow AT. 2018. Origin, reactivity, and bioavailability of mercury in wildfire ash. Environ Sci Technol. [accessed 2025 Jul 6];52:14149–14157. *https://doi.org/10.1021/acs.est.8b03729*

Ku P, Tsui MT–K, Uzun H, Chen H, Dahlgren RA, Hoang TC, Karanfil T, Zhong H, Miao A–J, Pan K, et al. 2024. Dominance of particulate mercury in stream transport and rapid watershed recovery from wildfires in Northern California, USA. Environ Sci Technol. [accessed 2025 Jul 6];58:22159–22169. *https://doi.org/10.1021/acs.est.4c09364*

Larsen RE, Shapero MWK, Striby K, Althouse LD, Meade DE, Brown K, Horney MR, Rao DR, Davy JS, Rigby CW, et al. 2021. Forage quantity and quality dynamics because of weathering over the dry season on California annual rangelands. Rangel Ecol Manag. [accessed 2025 Jul 6];76:150–156. *https://doi.org/10.1016/j.rama.2021.02.010*

Lawrence AJ, Matuch C, Hancock JJ, Rypel AL, Eliassen LA. 2022. Potential local extirpation of an imperiled freshwater mussel population from wildfire runoff. West N Am Nat. [accessed 2025 Aug 20];82(4):695–703. Available from: *https://bioone.org/journals/western-north-american-naturalist/volume-82/issue-4/064.082.0405/Potential-Local-Extirpation-of-an-Imperiled-Freshwater-Mussel-Population-from/10.3398/064.082.0405.short*

Lewis J. 1996. Turbidity-controlled suspended sediment sampling for runoff-event load estimation. Water Resour Res. [accessed 2025 Jul 6];32(7):2299–2310. Available from: *https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/96WR00991*

Li H–H, Tsui MT–K, Ku P, Chen H, Yin Z, Dahlgren RA, Parikh SJ, Wei J, Hoang TC, Chow AT, et al. 2022. Effects of forest fire ash on aquatic mercury cycling. Environ Sci Technol. [accessed 2025 Jul 6];56(16):11835–11844. *https://doi.org/10.1021/acs.est.2c01591*

Linley GD, Jolly CJ, Doherty TS, Geary WL, Armenteras D, Belcher CM, Bliege Bird R, Duane A, Fletcher M–S, Giorgis MA, et al. 2022. What do you mean, 'megafire'? Glob Ecol Biogeogr. [accessed 2025 Jul 6];31:1906–1922. Available from: *https://www.fs.usda.gov/rm/pubs_journals/2022/rmrs_2022_linley_g001.pdf*

Louhi P, Ovaska M, Mäki–Petäys A, Erkinaro J, Muotka T. 2011. Does fine sediment constrain salmonid alevin development and survival? Can J Fish Aquat Sci. [accessed 2025 Jul 6];68:1819–1826. *https://doi.org/10.1139/f2011-106*

Lund JR. 2016. California's agricultural and urban water supply reliability and the Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci. [accessed 2015 Jul 6];14(3). *https://doi.org/10.15447/sfews.2016v14iss3art6*

Luoma SN, Dahm CN, Healey M. Moore JN. 2015. Challenges facing the Sacramento–San Joaquin Delta: complex, chaotic, or simply cantankerous? San Franc Estuary Watershed Sci [accessed 2025 Jul 6];13(3). *http://doi.org/10.15447/sfews.2015v13iss3art7*

Magliozzi LJ, Matiasek SJ, Alpers CN, Korak JA, McKnight D, Foster AL, Ryan JN, Roth DA, Ku P, Tsui MTK, et al. 2024. Wildland–urban interface wildfire increases metal contributions to stormwater runoff in Paradise, California. Environ Sci—Proc Effects Impacts. [accessed 2025 Jul 6];26:4. *https://doi.org/10.1039/d3em00298e*

Maina FZ, Siirila–Woodburn ER. 2019. Watershed dynamics following wildfires: nonlinear feedbacks and implications on hydrologic responses. Hydrol Proc. [accessed 2025 Jul 6];34:33–50. *https://doi.org/10.1002/hyp.13568*

Marshall A, Waller L, Lekberg Y. 2016. Cascading effects of fire retardant on plant–microbe interactions, community composition, and invasion. Ecol Appl. [accessed 2025 Jul 6];26:996–1002. *https://doi.org/10.1890/16-0001.1*

Marvin–DiPasquale M, Alpers CN, Fleck JA. 2009. Mercury, methylmercury, and other constituents in sediment and water from seasonal and permanent wetlands in the Cache Creek Settling Basin and Yolo Bypass, Yolo County, California, 2005-06. Menlo Park (CA): US Geological Survey, US Department of the Interior. Open-File Report 2009-1182. 82 p. [accessed 2025 Jul 6]. Available from: *https://pubs.usgs.gov/of/2009/1182/of2009-1182.pdf*

Matthews KR, Berg NH. 1997. Rainbow trout responses to water temperature and dissolved oxygen stress in two southern California stream pools. J Fish Biol. [accessed 2025 Jul 6];50:50–67. *https://doi.org/10.1111/j.1095-8649.1997.tb01339.x*

McDowell RW, Simpson ZP, Ausseil AG, Etheridge Z, Law R. 2021. The implications of lag times between nitrate leaching losses and riverine loads for water quality policy. Sci Rep. [accessed 2025 Jul 6];11:16450. *https://doi.org/10.1038/s41598-021-95302-1*

McNabb DH, Swanson FJ. 1990. Effects of fire on soil erosion. In: Walstad JD, Radosevich, SR, Sandberg DV, editors. Natural and prescribed fire in the Pacific Northwest forests. Corvallis (OR): Oregon State University Press. p. 159–176. [accessed 2025 Jul 6]. Available from: *https://andrewsforest.oregonstate.edu/publications/1055*

Minear JT, Kondolf GM. 2009. Estimating reservoir sedimentation rates at large spatial and temporal scales: a case study of California. Water Resour Res. [accessed 2025 Jul 6];45: W12502. *https://doi.org/10.1029/2007WR006703*

Miralha L, Segura C, Bladon KD. 2024. Stream temperature responses to forest harvesting with different riparian buffer prescriptions in northern California, USA. Forest Ecol Manag. [accessed 2025 Jul 6];552:121581. *https://doi.org/10.1016/j.foreco.2023.121581*

Murphy P, Mass C. 2025. Weather associated with rapid-growth California wildfires. Weather Forecast. [accessed 2025 Jul 6];40:347–366. *https://doi.org/10.1175/WAF-D-24-0025.1*

Murphy SF, Alpers CN, Anderson CW, Banta JR, Blake JM, Carpenter KD, Clark GD, Clow DW, Hempel LA, Martin DA, et al. 2023. A call for strategic water-quality monitoring to advance assessment and prediction of wildfire impacts on water supplies. Front Water. [accessed 2025 Jul 6];5:1144225. *https://doi.org/10.3389/frwa.2023.1144225*

Murphy SF, McCleskey RB, Martin DA, Writer JH, Ebel BA. 2018. Fire, flood, and drought: extreme climate events alter flow paths and stream chemistry. J Geophys Res— Biogeosciences. [accessed 2025 Jul 6];123:2513–2526. *https://doi.org/10.1029/2017JG004349*

Murphy SF, Writer JH, McCleskey RB, Martin DA. 2015. The role of precipitation type, intensity, and spatial distribution in source water quality after wildfire. Environ Res Lett. [accessed 2025 Jul 6];10:084007. *https://doi.org/10.1088/1748-9326/10/8/084007*

Neto NDM, Evangelista H. 2022. Human activity behind the unprecedented 2020 wildfire in Brazilian wetlands (Pantanal). Front Environ Sci. [accessed 2025 Jul 6];10:888578. *https://doi.org/10.3389/fenvs.2022.888578*

Nichols J, Joseph E, Kaphle A, Tunby P, Rodriguez L, Khandelwal A, Reale J, Regier P, Van Horn DJ, Gonzalez–Pinzon R. 2024. Longitudinal propagation of aquatic disturbances following the largest wildfire recorded in New Mexico, USA. Nat Commun. [accessed 2025 Jul 6];15:7143). *https://doi.org/10.1038/s41467-024-51306-9*

North M. 2012. Riparian zones pose severe wildfire threat: efforts to protect streams may have the opposite effect. California Forests. [accessed 2025 Aug 20];(Spring):10–11. Available from: *https://northlab.faculty.ucdavis.edu/wp-content/uploads/sites/195/2019/03/Riparian-zone-severe-wildfire-California-Forests.pdf*

Nunes JP, Doerr SH, Sheridan G, Neris J, Santin C, Emelko MB, Silins U, Robichaud PR, Elliot WJ, Keizer J. 2018. Assessing water contamination risk from vegetation fires: challenges, opportunities, and a framework for progress. Hydrol Proc. [accessed 2025 Jul 6];32(5):687–694. *https://doi.org/10.1002/hyp.11434*

Odimayomi TO, Proctor CR, Wang QE, Sabbaghi A, Peterson KS, Yu DJ, Lee J, Shah AD, Ley CJ, Noh Y, et al. 2021. Water safety attitudes, risk perception, experiences, and education for households impacted by the 2018 Camp Fire, California.
Nat Hazards. [accessed 2025 Jul 6];108:947–975. *https://doi.org/10.1007/s11069-021-04714-9*

Oliver AA, Bogan MT, Herbst DB, Dahlgren RA. 2012. Short-term changes in stream macroinvertebrate communities following a severe fire in the Lake Tahoe basin, California. Hydrobiologia. [accessed 2025 Jul 6];694:117–130. Available from: *https://herbstlab.msi.ucsb.edu/pdfs/Oliver%20etal%202012_short%20term%20invert%20changes%20following%20fire.pdf*

Oliver AA, Reuter JE, Heyvaert AC, Dahlgren RA. 2012. Water quality response to the Angora Fire, Lake Tahoe, California. Biogeochemistry. [accessed 2025 Jul 6];111:361–376. *https://doi.org/10.1007/s10533-011-9657-0*

Olson NE, Boaggio KL, Rice RB, Foley KM, LeDuc SD. 2023. Wildfires in the western United States are mobilizing PM2.5-associated nutrients and may be contributing to downwind cyanobacteria blooms. Environ Sci—Proc Effects Impacts. [accessed 2025 Jul 6];25(6):1049–1066. *https://doi.org/10.1039/d3em00042g*

Parks SA, Miller C, Abatzoglou JT, Holsinger LM, Parisien M–A, Dobrowski SZ. 2016. How will climate change affect wildland fire severity in the western US? Environ Res Lett. [accessed 2025 Jul 6];11. *https://doi.org/10.1088/1748-9326/11/3/035002*

Paul MJ, LeDuc SD, Lassiter MG, Moorhead LC, Noyes PD, Leibowitz SG. 2022. Wildfire induces changes in receiving waters: a review with considerations for water quality management. Water Resour Res. [accessed 2025 Jul 6];58:e2021WR030699. *https://doi.org/10.1029/2021WR030699*

Pelletier N, Chételat J, Blarquez O, Vermaire JC. 2020. Paleolimnological assessment of wildfire-derived atmospheric deposition of trace metal(loid)s and major ions to subarctic lakes (Northwest Territories, Canada). J Geophys Res—Biogeosciences. [accessed 2025 Jul 6];125:e2020JG0055720. *https://doi.org/10.1029/2020JG005720*

Phillips C, Marden M, Basher L. 2015. Forests and erosion protection–getting to the root of the matter. N Zeal J For. [accessed 2025 Jul 6];60:11–15. Available from: *https://www.researchgate.net/publication/281411384_Phillips_CJ_Marden_M_Basher_L_2015_Forests_and_erosion_protection_-_getting_to_the_root_of_the_matter_New_Zealand_Journal_of_Forestry_602_11-15*

Power ME, Chandra S, Gleick P, Dietrich WE. 2024. Anticipating responses to climate change and planning for resilience in California's freshwater ecosystems. Proc Nat Acad Sci. [accessed 2025 Aug 20];121(32):e2310075121. *https://doi.org/10.1073/pnas.2310075121*

Preece EP, Cooke J, Plaas H, Sabo A, Nelson L, Paerl HW. 2024. Managing a cyanobacteria harmful algae bloom "hotspot" in the Sacramento–San Joaquin Delta, California. J Environ Manag. [accessed 2025 Jul 6];351:119606. *https://doi.org/10.1016/j.jenvman.2023.119606*

Reale JK, Archdeacon TP, Van Horn DJ, Gonzales EJ, Dudley RK, Turner TF, Dahm CN. 2021. Differential effects of a catastrophic wildfire on downstream fish assemblages in an aridland river. Aquat Ecol. [accessed 2025 Jul 6];55:483–500. *https://doi.org/10.1007/s10452-021-09839-4*

Reale JK, Van Horn DJ, Condon KE, Dahm CN. 2015. The effects of catastrophic wildfire on water quality along a river continuum. Freshw Sci. [accessed 2025 Jul 6];34(4):1426–1442. *https://doi.org/10.1086/684001*

Rhoades AM, Jones AD, Ullrich PA. 2018. The changing character of the California Sierra Nevada as a natural reservoir. Geophys Res Lett. [accessed 2025 Jul 6];45:13,008–13,019. *https://doi.org/10.1029/2018GL080308*

Robinne F-N, Hallema DW, Bladon KD, Flannigan MD, Boisramé G, Bréthaut CM, Doerr SH, Di Baldassarre G, Gallagher LA, Hohner AK, et al. 2021. Scientists' warning on extreme wildfire risks to water supply. Hydrol Process. [accessed 2025 Jul 6];35:e14086. *https://doi.org/10.1002/hyp.14086*

Rother DE, De Sales F, Stow D, McFadden J. 2022. Impacts of burn severity on short-term postfire vegetation recovery, surface albedo, and land surface temperature in California ecoregions. PLOS ONE. [accessed 2025 Jul 6];17(11):e0274428. *https://doi.org/10.1371/journal.pone.0274428*

Rust AJ, Hogue TS, Saxe S, McCray J. 2018. Post-fire water-quality response in the western United States. Intl J Wildl Fire. [accessed 2025 Jul 6];27:203–216. *https://doi.org/10.1071/wf17115*

Rust AJ, Saxe S, McCray J, Rhoades CC, Hogue TS. 2019. Evaluating the factors responsible for post-fire water quality response in forests of the western USA. Intl J Wildl Fire. [accessed 2025 Jul 6];28:769–784. *https://doi.org/10.1071/wf18191*

Safford HD, Paulson AK, Steel ZL, Young DJN, Wayman RB. 2022. The 2020 California fire season: a year like no other, a return to the past or a harbinger of the future? Glob Ecol Biogeogr. [accessed 2025 Jul 6];31:2005–2025. *https://doi.org/10.1111/geb.13498*

Sanders AM, Coble AA, Swartz AG, River M, James P, Warren DR. 2022. Heat and smoke from wildfires influence water temperature and dissolved oxygen levels in headwater streams. Freshw Sci. [accessed 2025 Jul 6];41:665–679. *https://doi.org/10.1086/722632*

Savage SM. 1974. Mechanism of fire-induced water repellency in soil. Soil Sci Society Am J. [accessed 2025 Aug 20];38:652–657. *https://doi.org/10.2136/sssaj1974.03615995003800040033x*

Scordo F, Chandra S, Suenaga E, Kelson SJ, Culpepper J, Scaff L, Tromboni F, Caldwell TJ, Seitz C, Fiorenza JE, et al. 2021. Smoke from regional wildfires alters lake ecology. Sci Rep. [accessed 2025 Jul 6];11:10922. *https://doi.org/10.1038/s41598-021-89926-6*

Scordo F, Sadro S, Culpepper J, Seitz C, Chandra S. 2022. Wildfire smoke effects on lake-habitat specific metabolism: toward a conceptual understanding. Geophys Res Lett. [accessed 2025 Jul 6];49:e2021GL097057. *https://doi.org/10.1029/2021GL097057*

Shakesby RA. 2011. Post-wildfire soil erosion in the Mediterranean: review and future directions. Earth-Sci Rev. [accessed 2025 Jul 6];105:71–100. *https://doi.org/10.1016/j.earscirev.2011.01.001*

Shen H, Dai Z, Zhang Q, Tong D, Su W–Q, Dahlgren RA, Xu J. 2024. Postfire phosphorus enrichment mitigates nitrogen loss in boreal forests. Environ Sci Technol. [accessed 2025 Jul 6];58:10611–10622. *https://doi.org/10.1021/acs.est.4c01662*

Shen H, Huang Y, Lin X, Dai Z, H Zhao, Su W–Q, Dahlgren RA, Xu J. 2025. Recoupling of soil carbon, nitrogen, and phosphorus cycles along a 30 year fire chronosequence in boreal forests of China. Environ Sci Technol. [accessed 2025 Jul 6];59:4432–4443. *https://doi.org/10.1021/acs.est.4c08790*

Sherson LR, Van Horn DJ, Gomez–Velez JD, Crossey LJ, Dahm, CN. 2015. Nutrient dynamics in an alpine headwater stream: use of continuous water quality sensors to examine responses to wildfire and precipitation events. Hydrol Process. [accessed 2025 Jul 6];29:3193–3207. *https://doi.org/10.1002/hyp.10426*

Smith HG, Sheridan GJ, Lane PNJ, Nyman P, Haydon S. 2011. Wildfire effects on water quality in forest catchments: a review with implications for water supply. J Hydrol. [accessed 2025 Jul 6];396:170–192. *https://doi.org/10.1016/j.jhydrol.2010.10.043*

Smith J, Eggleston E, Howard MDA, Ryan S, Gichuki J, Kennedy K, Tyler A, Beck M, Huie S, Caron DA. 2023. Historic and recent trends of cyanobacterial harmful algal blooms and environmental conditions in Clear Lake, California: a 70-year perspective. Elementa—Sci Anthrop. [accessed 2025 Jul 6];11:00115. *https://doi.org/10.1525/elementa.2022.00115*

Smits AP, Scordo F, Tang M, Cortés A, Farruggia MJ, Culpepper J, Chandra S, Jin Y, Valbuena SA, Watanabe S, et al. 2024. Wildfire smoke reduces lake ecosystem metabolic rates unequally across a trophic gradient. Commun Earth Environ. [accessed 2025 Jul 6];5:265. *https://doi.org/10.1038/s43247-024-01404-9*

Solomon GM, Hurley S, Carpenter C, Young TM, English P, Reynolds P. 2021. Fire and water: assessing drinking water contamination after a major wildfire. Environ Sci Technol—Water. [accessed 2025 Jul 6];1:1878–1886. *https://doi.org/10.1021/acsestwater.1c00129*

Steel ZL, Safford HD, Viers JH. 2015. The fire frequency–severity relationship and the legacy of fire suppression in California forests. Ecosphere. [accessed 2025 Jul 6];6:1–23. *https://doi.org/10.1890/ES14-00224.1*

Stephens SL, Burrows N, Buyantuyev A, Gray RW, Keane RE, Kubian R, Liu S, Seijo F, Shu L, Tolhurst KG, et al. 2014. Temperate and boreal forest mega-fires: characteristics and challenges. Front Ecol Environ. [accessed 2025 Jul 6];12(2):115–122. *https://doi.org/10.1890/120332*

Swarowsky A, Dahlgren RA, O'Geen AT. 2012. Linking subsurface lateral flowpath activity with streamflow characteristics in a semiarid headwater catchment. Soil Sci Soc Am J. [accessed 2025 Jul 6];76:532–547. *https://doi.org/10.2136/sssaj2011.0061*

Thomas RB 1985. Estimating total suspended sediment yield with probability sampling. Water Resour Res. [accessed 2025 Jul 6];21(9):1381–1388. *https://doi.org/10.1029/WR021i009p01381*

Uzun H, Dahlgren RA, Olivares C, Erdem CU, Karanfil T, Chow AT. 2020. Two years of post-wildfire impacts on dissolved organic matter, nitrogen, and precursors of disinfection by-products in California stream waters. Water Res. [accessed 2025 Jul 6];181:115891. *https://doi.org/10.1016/j.watres.2020.115891*

Verkaik I, Rieradevall M, Cooper SD, Melack JM, Dudley TL, Prat N. 2013. Fire as a disturbance in mediterranean climate streams. Hydrobiologia. [accessed 2025 Jul 6];719(1):353–382. *https://doi.org/10.1007/s10750-013-1463-3*

Vila–Escale M. 2009. Efectes d'un incendi forestal en una riera mediterrania (Sant Llorenç¸ del Munt, 2003) [dissertation]. [Barcelona (Spain)]: Universitat de Barcelona. 222 p.

Vitousek PM, Gosz JR, Grier CC, Melillo JM, Reiners WA, Todd RL. 1979. Nitrate losses from disturbed ecosystems. Science. [accessed 2025 Jul 6];204:469–474. *https://doi.org/10.1126/science.204.4392.469*

Volkmar EC, Henson SS, Dahlgren RA, O'Geen AT, Van Nieuwenhuyse EE. 2011. Diel patterns of algae and water quality constituents in the San Joaquin River, California, USA. Chem Geol. [accessed 2025 Jul 6];283:56–67. *https://doi.org/10.1016/j.chemgeo.2010.10.012*

Wang J–J, Dahlgren RA, Erşan MS, Karanfil T, Chow AT. 2016. Temporal variations of disinfection byproduct precursors in wildfire detritus. Water Res. [accessed 2025 Jul 6];99:66–73. *https://doi.org/10.1016/j.watres.2016.04.030*

Westerling AL. 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Philos Trans R Soc B. [accessed 2025 Jul 6];371:20150178. *https://doi.org/10.1098/rstb.2015.0178*

Westerling AL. 2018. Wildfire simulations for California's Fourth Climate Change Assessment: projecting changes in extreme wildfire events with a warming climate. (A report for California's Fourth Climate Change Assessment.) This work was supported by the California Energy Commission, Agreement Number 500-14005. [accessed 2025 Jul 6]. 57 p. Available from: *https://www.energy.ca.gov/sites/default/files/2019-11/Projections_CCCA4-CEC-2018-014_ADA.pdf*

Western Fire Chiefs Association. c2022. California fire season: in-depth guide. [accessed 2025 Jul 6]. Available from: *https://wfca.com/wildfire-articles/california-fire-season-in-depth-guide/#pp-toc-6x9tjk18rl5u-anchor-2*

White I, Wade A, Worthy M, Mueller N, Daniell T, Wasson R. 2006. The vulnerability of water supply catchments to bushfires: effects of the January 2003 wildfires on the Australian Capital Territory. Austr J Water Resour. [accessed 2025 Jul 6];10(2):179–194. *https://doi.org/10.1080/13241583.2006.11465291*

Williams AP, Abatzoglou JT, Gershunov A, Guzman–Morales J, Bishop DA, Balch JK, Lettenmaier DP. 2019. Observed impacts of anthropogenic climate change on wildfire in California. Earth's Future. [accessed 2025 Jul 6];7:892–910. *https://doi.org/10.1029/2019EF001210*

Wine ML, Cadol D. 2016. Hydrologic effects of large southwestern USA wildfires significantly increase regional water supply: fact or fiction? Environ Res Lett. [accessed 2025 Jul 6];11:085006. *https://doi.org/10.1088/1748-9326/11/8/085006*

Young AM, Skelly KT, Cordeira JM. 2017. High-impact hydrologic events and atmospheric rivers in California: an investigation using the NCEI storm events database. Geophy Res Lett. [accessed 2025 Jul 6];44:3393–3401. *https://doi.org/10.1002/2017GL073077*