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A call for strategic water-quality monitoring to advance assessment and prediction of wildfire impacts on water supplies

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Wildfires pose a risk to water supplies in the western U.S. and many other parts of the world, due to the potential for degradation of water quality. However, a lack of adequate data hinders prediction and assessment of post-wildfire impacts and recovery. The dearth of such data is related to lack of funding for monitoring extreme events and the challenge of measuring the outsized hydrologic and erosive response after wildfire. Assessment and prediction of post-wildfire surface water quality would be strengthened by the strategic monitoring of key parameters, and the selection of sampling locations based on the following criteria: (1) streamgage with pre-wildfire data; (2) ability to install equipment that can measure water quality at high temporal resolution, with a focus on storm sampling; (3) minimum of 10% drainage area burned at moderate to high severity; (4) lack of major water management; (5) high-frequency precipitation; and (6) availability of pre-wildfire water-quality data and (or) water-quality data from a comparable unburned basin. Water-quality data focused on parameters that are critical to human and (or) ecosystem health, relevant to water-treatment processes and drinking-water quality, and (or) inform the role of precipitation and discharge on flow paths and water quality are most useful. We discuss strategic post-wildfire water-quality monitoring and identify opportunities for advancing assessment and prediction. Improved estimates of the magnitude, timing, and duration of post-wildfire effects on water quality would aid the water resources community prepare for and mitigate against impacts to water supplies.

KEYWORDS

wildfire, wildland fire, post-wildfire, burned area, water supplies, water availability, disturbance, water quality

1. Introduction

Wildfires are a natural process in many ecosystems, but their size and severity have increased substantially over the past few decades (Juang et al., 2022; Shuman et al., 2022) and are now widely recognized as a critical risk to water supplies in the western U.S. and many other parts of the world (Bryson, 2021; Fountain, 2021; Nilsen, 2022). Wildfires can lead to increased runoff, erosion, and conveyance of sediment, ash, pollutants, and debris to surface water, resulting in decreased water quality, loss of reservoir storage capacity, stream habitat degradation, and increased treatment costs for drinking water providers (Emelko et al., 2011; Smith et al., 2011; Sham et al., 2013; Bladon et al., 2014; Martin, 2016; Rhoades et al., 2019b). The range of water-quality effects, however, has varied widely, from no noticeable change to orders of magnitude increases in concentrations and yields of sediment, dissolved organic carbon (DOC), nitrate, phosphorus, metals, and other constituents (Rust et al., 2018; Paul et al., 2022). Water providers, reservoir operators, land managers, and emergency response agencies would benefit from improved assessment and prediction of the character, magnitude, and duration of water-quality impacts after wildfire in watersheds across a wide range of ecoregions. A lack of adequate pre- and post-wildfire water-quality data hinders model calibration and adaptation (Basso et al., 2022), assessment of post-wildfire recovery (Hampton et al., 2022), and understanding how wildfires will affect regulatory requirements (Paul et al., 2022). Here we describe a path forward for strategic, consistent post-wildfire water-quality data collection for surface water that, when deployed across a range of ecosystems, will lead to vastly improved assessment and prediction of impacts of wildfire on water supplies.

2. Gaps and barriers in existing post-wildfire water-quality data

Post-wildfire water-quality studies in the past, when conducted, have typically been performed on an *ad-hoc*, inconsistent basis driven by a local need, available funding, and (or) a particular research question. Therefore, data sets with consistent objectives, approaches, and constituents are rare. The dearth of consistent data is largely related to the challenges in obtaining funding to study rare events (Smith et al., 2011; Patrick et al., 2022) and in measuring the often outsized hydrologic and erosive response to post-wildfire runoff and flooding. Funds related to wildfires were long focused on immediate risk to life and property, with water supplies only recently gaining public attention (Bladon et al., 2014; Martin, 2016; Robinne et al., 2021). The most severe water-quality impacts are often delayed until subsequent high-intensity rainstorms, which can occur months to years after the wildfire (Murphy et al., 2015), by which time funding opportunities and public attention have diminished. Evaluating the effects of wildfires is complicated by a general lack of stream discharge and water-quality data in forested headwaters (Bishop et al., 2008; Krabbenhoft et al., 2022) to provide a pre-wildfire comparison. In addition, because wildfires can reduce the threshold precipitation intensity at which overland flow occurs, post-wildfire stream discharge and sediment concentrations can be orders of magnitude greater than they would have been for similar storms pre-wildfire (Wondzell and King, 2003; Murphy et al., 2015), which poses challenges to current monitoring capabilities. As a result of these challenges, there are numerous gaps in post-wildfire water-quality data (Yu and Cheng, 2008; Rust et al., 2018; Basso et al., 2022; Hampton et al., 2022; Paul et al., 2022; Robinne et al., 2022; Raoelison et al., 2023), as shown in Figure 1.

Data-related gaps highlighted in Figure 1 result in a lack of consistent data needed for the development of models and assessments that could provide actionable guidance for water-supply agencies that is broadly applicable across regions. Data consistency issues also hinder comparisons between different studies, and derived estimates of the magnitude, timing, and duration of post-wildfire effects on water quality have high uncertainty.

3. Proposed strategy

Closing the aforementioned water-quality data gaps requires strategic monitoring to produce consistent, unified datasets. Optimal collection of these new datasets involves careful selection of sampling locations and measurement of consistent parameters at similar temporal scales. We present the following strategy for selecting locations and methodologies for data collection that enable identification of regional insights into effects of wildfire on surface water quality.

3.1. Monitoring locations

Post-wildfire water-quality data are needed from sites with a diversity in climate, land use, geology, and vegetation to build a foundation for discerning regional differences in effects on hydrogeochemical and ecological systems. With hundreds of wildfires burning U.S. watersheds each year, it would be impossible to monitor every stream within or downstream of a burned area. Selection of monitoring locations based on the following optimal criteria would strengthen assessment and prediction of post-wildfire water quality (Figure 1):

- *Active (or recently active) streamgage with pre-fire data.* Discharge is critical to understanding water quality. Ideally, the site would have a stream discharge record longer than 10 years, collected within the last 30 years, to allow separation of climate variability from wildfire impacts.
- *Continuous water-quality sensors and storm-sampling equipment can be co-located with streamgage and can be accessed frequently.* Due to the critical role that storm events play in the transport of post-wildfire ash and sediment, high-frequency data collection that covers all ranges of stream discharge is most useful. It must be possible to access the equipment safely in all weather conditions.
- *At least 10% of watershed is burned at moderate to high severity.* Many studies have indicated that forest disturbances affect watershed response, and a range of disturbance thresholds has been reported in the literature. For example, some studies

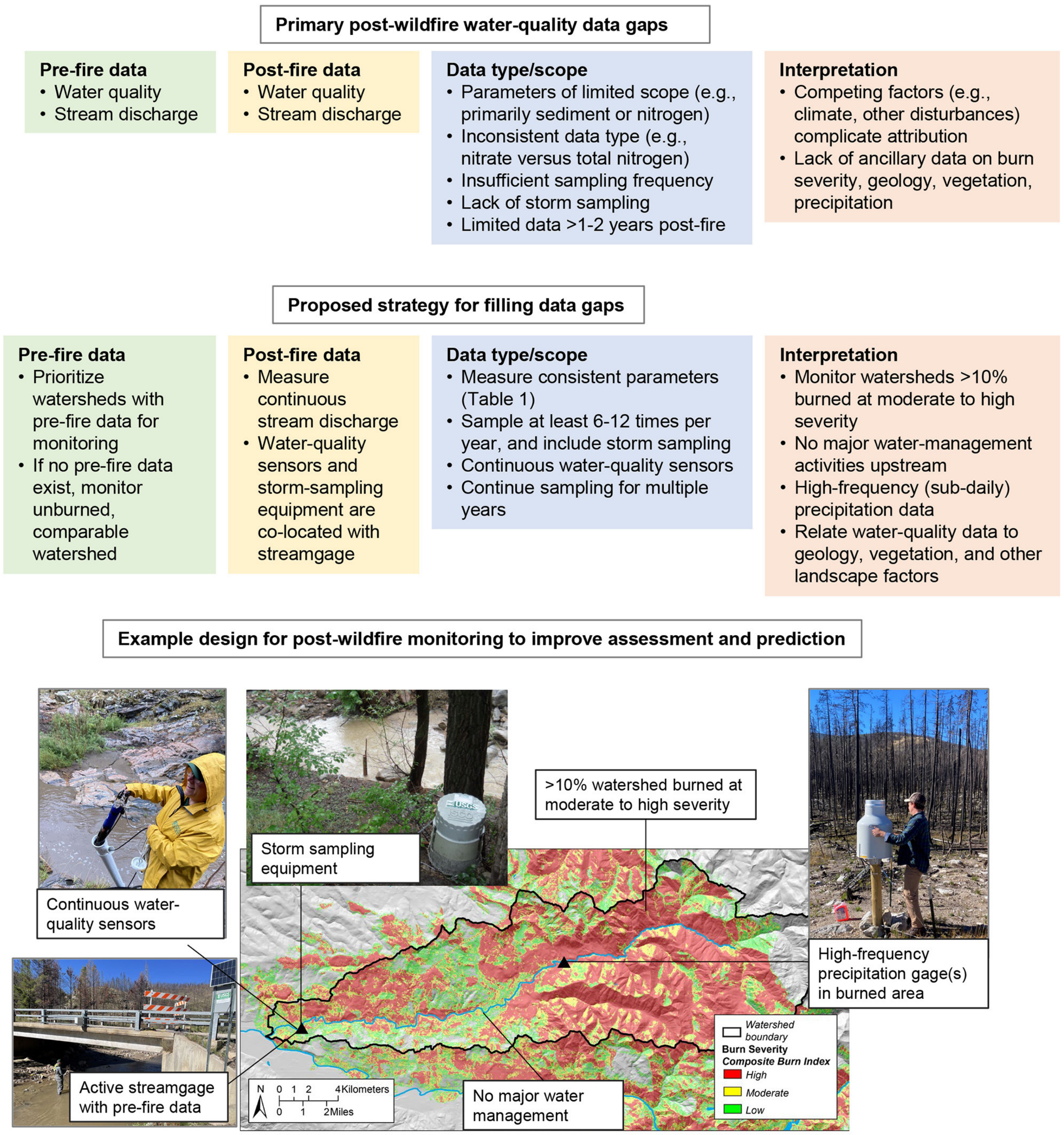

FIGURE 1
Post-wildfire water-quality gaps and proposed gap-filling strategy. [Composite burn index (Key and Benson, 2006) rates burn severity for substrates (litter, duff, fuel, and soil) and vegetation on a continuous scale from 0 (unburned) to 3 (high burn severity). Map prepared by Max Schwid; photographs by Sheila Murphy and Mike Kohn].

documented effects on annual water yield when 20% or more of a watershed is disturbed (Bosch and Hewlett, 1982; Wine and Cadol, 2016; Hallema et al., 2018); other work has reported that as little as 7–10% of watershed disturbance may cause a hydrologic effect (Buma and Livneh, 2017; Beyene et al., 2021). The proposed minimum percentage of the watershed burned at moderate to high severity would allow us to identify thresholds for post-wildfire water-quality effects across a range of constituents and ecoregions.

- *Watershed has no major water-management activities upstream of the monitoring location.* Water management, including diversions, reservoirs, and wastewater plants, can obscure wildfire impacts to stream discharge or water quality. While monitoring wildfire-affected basins with water resources management would be beneficial to provide critical operational guidance to water providers, active pre-wildfire or post-wildfire water management can make data less useful for model and assessment development.

- *High-frequency (sub-daily) precipitation data can be obtained within the burned area.* These data would allow correlation of water quality with hydrologic drivers, such as rainfall intensity (Murphy et al., 2015), and comparison to pre-wildfire rainfall-runoff response. Precipitation frequency estimates (Perica et al., 2013), and (or) gridded data, such as PRISM (Daly et al., 1994) or Daymet (Thornton et al., 2012) may be used to guide precipitation gage locations and density. However, gridded data usually lack sufficient temporal resolution and are less accurate in areas of steep mountains and lack of precipitation gages (Murphy et al., 2017), which is a common scenario in burned forests. On-the-ground precipitation monitoring can also fill gaps in weather radar or better capture high-intensity rainfall (e.g., Nikolopoulos et al., 2015; Bernard and Gregoretti, 2021).
- *Pre-wildfire water-quality data and (or) water-quality data from a comparable unburned basin are available.* Pre-wildfire water-quality data, collected for many years and across a range of stream discharge, would best enable the separation of the effect of wildfire from other climate or landscape factors. However, these data are scarce (Rust et al., 2018; Raoelison et al., 2023), and requiring such data would eliminate most watersheds from selection. Water-quality data collected on the same stream, upstream from the burned area, and (or) from a nearby, unburned watershed with similar landscape (land cover, geology, vegetation, etc.) and climate can also aid in the interpretation of post-wildfire effects (Hewlett, 1971; Rice, 1979).

3.2. Monitoring design and frequency

A combination of continuous in-stream sensors and water-quality samples (across a range of discharge values) is needed to capture the full range of post-wildfire response and to facilitate diagnosing connections and dependencies between watershed processes and constituent fate and transport. In-stream sensors can provide high-frequency data (depending on local precipitation regime, 1–15-min measurement intervals may be needed) for certain constituents of interest, are valuable for capturing transient events, and require minimal field staff. Water-quality samples are needed to capture a broader range of parameters, and to correlate with and correct sensor data; for example, fluorescent dissolved organic matter measurements must be corrected for interference in highly turbid waters (Saraceno et al., 2017). Storm sampling with automatic samplers (triggered by water level and (or) turbidity) allows the collection of water samples during high-flow events that may be too dangerous or short-lived to collect with routine sampling, and can capture very turbid events, when sensors can be damaged and (or) monitoring capabilities can be exceeded. Following best practices for water-quality sample collection and processing, such as the U.S. Geological Survey's National Field Manual for the Collection of Water-Quality Data (U. S. Geological Survey, 2018), ensures site intercomparability. Hydrologic and geomorphic response can be amplified after wildfire; thus, the use of rugged, secure, non-contact, and (or) inexpensive monitoring equipment can reduce the financial risk of equipment damage or loss. Rust et al. (2018) advocated for collection of post-wildfire water-quality data at a frequency of at least six times per year and ideally 12 times per year; we agree that 12 samples per year, across a range of hydrologic conditions, is an ideal minimum value, but we believe that storm sampling is critical, with at least 30–50% of the samples collected during storm events. Perennial streams generally have greater relevance to water supply, and thus would serve as an initial focus.

Ideally, monitoring stream discharge and water quality would begin immediately after wildfire and continue for many years. Magnitudes of response for certain constituents of concern, such as nitrate, DOC, and some metals are typically greatest in the initial rainstorms ("first flush") following wildfire containment; thus, depending on the timing of wildfire and seasonality of precipitation in the ecoregion, equipment deployment as soon as possible after the wildfire provides the best opportunity to capture initial responses. However, we acknowledge the immense challenge this can pose because of difficulty in obtaining appropriate access and funding after wildfire (Smith et al., 2011; Patrick et al., 2022). Post-wildfire hydrologic and water-quality effects tend to be greatest in the first 3 years after wildfire, though in some regions debris flow risk (and thus sediment transport) may increase 5–10 years post-wildfire due to root decomposition (Wondzell and King, 2003). Very few studies have monitored post-wildfire water quality for >5 years (Rust et al., 2018; Hampton et al., 2022). Thus, maintaining post-wildfire water-quality monitoring for longer periods would allow us to improve our ability to assess "recovery," which will vary by constituent (Minshall et al., 1989; Silins et al., 2009; Emelko et al., 2016; Rhoades et al., 2019a) and ecoregion.

3.3. Water-quality parameters and relevant measurements

The most useful water-quality parameters to measure after wildfire are those that are critical to human and (or) ecosystem health, relevant to water-treatment processes and drinking-water quality, have a watershed-specific regulatory requirement, and (or) inform the role of precipitation and discharge on flow paths and water quality. Parameter selection must balance the collection of essential data with fiscal and practical constraints; therefore, we have divided these parameters into two tiers. Tier one parameters are considered the highest priority for assessing and modeling impacts of wildfire on water quality; tier two parameters would provide additional information relevant to water treatment, aquatic life, and (or) flow paths and lay the groundwork for next-generation modeling capabilities, but substantially increase monitoring costs.

Additional parameters not listed in (Table 1) may also be desired due to local circumstances and (or) stakeholder needs, or to inform specific types of models, but can be cost-prohibitive. Parameters that could inform the evaluation of water-quality and ecosystem impacts include organic contaminants (e.g., polycyclic aromatic hydrocarbons [PAHs]), and other compounds that may be present in the wildland/urban interface (Paul et al., 2022). In addition to changes in DOC concentrations, carbon

TABLE 1 Critical parameters to measure after wildfire to improve assessment and prediction of water quality.

Tier	Setting	Parameter	Continuous (C) or discrete (D)	Relevance
1 (optimal minimum)	Surface water (field)	Stream discharge[a]	C	Relate hydrology to water quality, calculate loads
		Water temperature	C/D	Aquatic life, interpretation of other parameters
		pH	C/D	Aquatic life, metal bioavailability, interpretation of other parameters
		Specific conductance	C/D	Indicator of salinity and dissolved solids concentration, water treatment
		Turbidity	C/D	Water treatment, reservoir operations, aquatic life
		Dissolved oxygen	C/D	Aquatic life, biogeochemical cycling, risk of harmful algal blooms (HABs)
	Surface water (laboratory)	Turbidity	D	Calibrate continuous turbidity data, relate to sediment concentration
		Suspended sediment	D	Relate to turbidity data to estimate continuous sediment concentrations
		Silt/sand break	D	Informs relation of turbidity to sediment
		Nitrogen species (total, ammonium, nitrate)[b]	D	Water supply, ecosystems, HABs
		Phosphorus (total and ortho)[b]	D	Water supply, ecosystems, HABs
		Dissolved organic carbon	D	Water treatment and metal bioavailability
	Landscape	Precipitation[c]	C	Relate precipitation amount and intensity to hydrology and water quality
2 (additional parameters relevant for water treatment, aquatic life, and (or) flow paths)	Surface water (field)	Fluorescent dissolved organic matter (fDOM) sensor	C	Relate to dissolved organic carbon measurements to estimate continuous concentrations
		Nitrate sensor	C	Relate to nitrate measurements to estimate continuous concentrations
	Surface water (laboratory)	Major cations (Ca, K, Mg, Na)	D	Metal bioavailability, informs estimates of salinity from specific conductance
		Major anions (Cl, SO_4)	D	Water treatment, informs estimates of salinity from specific conductance
		Alkalinity	D	Metal bioavailability, informs estimates of salinity from specific conductance
		Metals and metalloids	D	Water treatment and aquatic life
		Ultraviolet absorbance at 254 nm wavelength	D	Calculate specific ultraviolet absorbance (water treatment)
		Silica	D	Inform hydrologic flow paths
		Stable isotopes of water	D	Inform hydrologic flow paths

[a] Non-contact methods may be needed in some environments, because traditional in-stream equipment can be damaged during post-wildfire flooding.

[b] Additional parameters (such as nitrite, dissolved organic nitrogen, and dissolved organic phosphorus) can also be useful, depending on specific needs.

[c] Ideally both tipping-bucket rain gage, for rainfall intensity, and total precipitation gage, so that snow is included. In mountainous areas with convective storms, a spatially dense rain-gage network may be needed.

character can be altered by wildfire, with implications for potential disinfection byproducts in drinking water (Wang et al., 2015; Hohner et al., 2016); therefore, carbon spectral fluorescence fingerprinting (Carpenter et al., 2022) could aid in assessing impacts of wildfire on drinking water supplies. Studies of fish populations, macroinvertebrate populations, stream metabolism rates, and harmful algal blooms (HABs), particularly regarding physiological tools and biomarkers, would assist in modeling wildfire effects on stream ecosystems (Gomez Isaza et al., 2022).

Post-wildfire assessment and modeling efforts would also be improved by collecting more accurate measurements of spatial precipitation patterns [by deploying precipitation gages or weather radar (NOAA-USGS Debris Flow Task Force, 2005)] and runoff events [measurement of both stage and velocity by noncontact radar provides useable hydraulic information when channel morphology changes rapidly (Fulton et al., 2020)], along with measurements that inform infiltration and flow paths [e.g., air temperature, soil-hydraulic properties controlling infiltration (Ebel, 2013, 2020), soil moisture sensors, and cameras aimed at burned hillslopes]. Detailed analysis of local geology and soils, vegetation types, and burn severity (Cerrato et al., 2016; Rahman et al., 2018) facilitates identification of critical drivers in different ecosystems. Finally, high-resolution, repeat land surface measurements derived from remote sensing datasets (including imagery or light detection and ranging (LiDAR) datasets) would further improve understanding of post-wildfire runoff and land surface change (East et al., 2021; Morell et al., 2021; Rengers et al., 2021), and impacts on post-wildfire water quality.

4. Opportunities

While the post-wildfire water-quality datasets described here would serve as the keystone for assessment and prediction of wildfire impacts on water supplies, there are many additional opportunities for improving our understanding of the nexus of wildfire, water, and society (Martin, 2016). Water-quality monitoring in watersheds that are vulnerable to wildfire, including parameters listed in (Table 1), would provide critical baseline data for assessing how wildfires impact watersheds. Improved post-wildfire water-modeling capacity, driven by data integration that reduces prediction uncertainty, would further advance the ability of the wildfire-science community to provide actionable intelligence for water supply planning and protection (e.g., Neris et al., 2021; Nyman et al., 2021; Steblein et al., 2021; Robinne et al., 2022). Remotely sensed characterization of post-wildfire water quality could provide a globally available sentinel of water-supply hazards. Recent work has shown that satellite remote sensing can provide spatial and temporal estimates of post-wildfire turbidity (Cira et al., 2022) and phytoplankton blooms (Tang et al., 2021). Post-wildfire changes in nutrient loads may alter chlorophyll-*a*, colored dissolved organic matter, and HABs in receiving waters that could be detected by satellite remote sensing (Cira et al., 2022).

Key near-term opportunities from strategic post-wildfire water-quality monitoring include:

- Identifying regional factors that dampen or amplify the effects of wildfire on water quality to provide rapid, actionable guidance for water-supply planning and protection.
- Integrating water-quality datasets into model development and evaluation.
- Linking *in-situ* water-quality measurements with remotely sensed water-quality indicators.
- Advances in in-stream sensor technology during high-turbidity events.

The next generation of strategic post-wildfire water-quality monitoring can extend beyond the priorities outlined here. We focus on in-stream processes, but understanding wildfire effects on reservoirs is an important next step in post-wildfire monitoring (Nunes et al., 2018; Basso et al., 2021; Paul et al., 2022). Groundwater, which supplies water to over 2 billion people and accounts for up to a third of global water withdrawals (Famiglietti, 2014), can be detrimentally affected by wildfire (Mansilha et al., 2020), yet there is almost no data or guidance on potential wildfire impacts on public or private supply wells. The present state of knowledge cannot provide reliable estimates of the downstream water-quality extent beyond the burned area (Martin, 2016), yet this guidance is clearly needed. Finally, we have focused on perennial streams due to their greater importance to water supplies, but intermittent and ephemeral streams can also convey sediment and other water-quality constituents to streams following wildfire (MacNeille et al., 2020) and thus can be important to study in some basins.

Wildfire is often not the sole terrestrial disturbance affecting water-supply watersheds; pre- and post-wildfire logging, reforestation, mining, and other activities can confound interpretations of wildfire impacts (e.g., Silins et al., 2009; Harrison et al., 2014; Rhoades et al., 2018; Stevens-Rumann et al., 2018; Murphy et al., 2020; Burke et al., 2021), especially when such disturbances overlap in space and time. Compound stressors can extend to atmospheric processes such as elevated wet and dry deposition of constituents before wildfire (Riggan et al., 1994; Burke et al., 2010; Heindel et al., 2022) and smoke effects (Williamson et al., 2016; Evans et al., 2021; Boyer et al., 2022). Climate variability and change also confound detecting wildfire effects, and future shifts in precipitation regimes (Touma et al., 2022) may affect constituent mobilization. The need for tracking the source and transformation of constituents from hillslopes to channels to lentic water bodies has been identified as a critical gap (e.g., Nunes et al., 2018).

Priority areas for longer-term post-wildfire water-quality monitoring and assessment include:

- Tracking constituent sources from hillslopes and into channels, including in-channel sources such as stored sediment or hyporheic exchange processes, and their transformation during transport.
- Connecting post-wildfire stream water quality to processes and conditions in downstream receiving waters such as reservoirs and estuaries, thus linking hillslopes, lotic, and lentic water bodies for different constituents and river corridor structures.
- Measuring wildfire effects on groundwater quantity and quality.
- Separating out the confounding influence of multiple, overlapping disturbances and land-use legacies.
- Establishing mechanisms for adequately funding post-wildfire monitoring campaigns.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

SM and BE conceptualized the paper. SM led the design and drafting of the manuscript with BE and DM. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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