ENVIRONMENTAL STUDIES

Building water resilience in the face of cascading wildfire risks

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Severe wildfire is altering the natural and the built environment and posing risks to environmental and societal health and well-being, including cascading impacts to water systems and built water infrastructure. Research on wildfire-resilient water systems is growing but not keeping pace with the scale and severity of wildfire impacts, despite their intensifying threat. In this study, we evaluate the state of knowledge regarding wildfire-related hazards to water systems. We propose a holistic framework to assess interactions and feedback loops between water quality, quantity, and infrastructure hazards as determinants of post-fire water availability and access. Efforts to address the evolving threat of wildfires to water systems will require more interdisciplinary research on the complex relationships shaping wildfire's threat to water availability and access. To support this, we need reliable long-term data availability, consistent metrics, greater research in shared contexts, more extensive research beyond the burn area, and multistakeholder collaboration on wildfire risks to water systems.

INTRODUCTION

Wildfires are becoming increasingly frequent and destructive across the globe because of a confluence of factors, including climate change, fire suppression regimes, land management policies, and human encroachment into wildlands (*1*–*6*). The rising occurrence of drought due to climate change amplifies these effects, which also increasingly stresses natural hydrologic systems and water supplies. In the United States, forests make up 36% of the total land area but contribute 50% of the total surface water yield, and federally owned forests supply the majority of water for populations in the West (*7*, *8*). Within these forested watersheds that supply drinking water, an average of 29% of the forested areas are at high or very high risk of fire (*9*). The repeated occurrences of wildfires in recent years have revealed water system vulnerabilities and subsequent impacts of hazardous wildfires [e.g., (*10*, *11*)]. Our water supply networks, both natural hydrologic systems and built infrastructure, are at risk of degradation, threatening environmental and societal health and well-being. Current research in understanding, developing, and implementing practices that promote fire-resilient water systems is not keeping pace with the scale and severity of the threat.

Severe wildfires can lead to adverse effects on the local environment during and after the blaze. However, the movement of air and water extends these impacts beyond the immediate burn area, with consequences for rural and downstream communities. Sediment and contaminants released from vegetation, soils, and human structures/built environment during fire events are eventually flushed from the burn area or deposited atmospherically into surface waters [e.g., (*12*–*16*)]. In addition, wildfires may disrupt the normal ecosystem processes that maintain the water balance, resulting in elevated runoff and flood risk [e.g., (*17*–*19*)]. The infrastructure necessary to treat and distribute water to various communities may also suffer direct or indirect damage as a result of wildfires (*11*, *20*).

The need for more advanced knowledge of these threats and effective mitigation strategies was made apparent during the 2018 and 2020 fire seasons in the western United States which caused multiple water system challenges. Fires and subsequent storms, floods, and debris flows resulted in water quality declines, water and hydroelectric service interruptions, and damage to critical infrastructure. Water managers in affected areas were forced to periodically suspend water intake from local rivers following fire events when the levels of sediment and contamination were deemed too extreme for treatment facilities (*21*). As a result of these and previous fire seasons, in some fire-prone regions, a few water agencies have started to invest heavily in actions that mitigate wildfire-related threats to the watersheds that supply their drinking water (*22*).

Unfortunately, resource allocation and spending for water supply systems and infrastructure protection have not grown in parallel to the risk and are highly variable between communities (*23*, *24*). Some communities have developed detailed source water protection strategies [e.g., (*25*, *26*)], yet many have not adequately assessed and planned for the risks posed by wildfires to their water systems (*24*). Further, not all source water protection strategies provide adequate consideration of the multiple threats wildfires present to water systems [e.g., (*27*)]. Fragmented knowledge surrounding the threats wildfires pose to water systems creates added challenges for water and fire managers seeking to appropriately mitigate and respond to these threats.

The expansion of the wildland-urban interface (WUI) in recent decades has further challenged forest and water managers. The encroachment of urban communities into wildland areas has contributed to substantially elevated wildfire risk and increased human exposure to post-fire water hazards, such as flooding and water distribution network contamination (*4*). Resource constraints have made it difficult for forest management agencies to proactively mitigate increasing fire risk in the rapidly expanding WUI (*28*). However, spending on wildfire response is at an all-time high.

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Federal wildfire suppression costs have gone from an annual average of over $426 million to $1.7 billion from 2000 to 2021 (*29*).

These resource constraints, coupled with continually evolving wildfire-related risks, have led to many challenges in protecting threatened water systems. The secondary post-fire hazards that threaten water systems continue to grow, and as these hazards increasingly co-occur, reoccur, and propagate across spatial and temporal scales, the complexity of the management landscape grows as well. To navigate this mounting complexity, a holistic approach can enable effective assessment, mitigation, and responses to wildfire-related risks to water systems. Here, we aim to unify the literature spanning the water system impacts of wildfire to inform assessments of water system vulnerability to the hazard of wildfire.

In this study, we conduct a systematic review to evaluate the current state of knowledge regarding wildfire-related hazards to water quality, water quantity, and water infrastructure. We provide an overview of the literature, including both peer-reviewed and gray literature, and identify the current state of knowledge on the interconnected wildfire impacts to the water system. Next, we assess how changes to the biogeophysical characteristics of a watershed can lead and contribute to these hazards to shed light on the land use planning and management efforts that can mitigate these risks. We present a holistic framework that identifies the multiple linkages and feedback loops between wildfire and water availability and propose several strategies to support wildfire and water resilience at the WUI and beyond.

RESULTS

The state of the literature

We reviewed 212 publications (177 peer-reviewed publications and 35 gray literature) to assess the state of the knowledge for wildfire hazards and their linkages to water quantity, quality, and infrastructure. Of the 177 peer-reviewed publications, 120 featured named, distinct wildfire events. Eighteen named wildfires appeared in three or more of the peer-reviewed studies and are summarized in table S1. The United States was overrepresented in the reviewed content representing 111 of the 120 named wildfires. There was more geographical diversity in the reviewed gray literature spanning across the United States, Canada, and Australia. All publications were written between 1999 and 2022, although the publication date was not used in the inclusion criteria (Fig. 1). We classified water supply systems as source water (i.e., natural infrastructure), which included water quality and quantity parameters, and water infrastructure (i.e., built infrastructure). Nearly one-third of the peer-reviewed publications investigated impacts to water quantity and water quality, respectively, while fewer than 3% examined the effects of wildfire on built water infrastructure alone. The gray literature publications, in contrast, frequently addressed all three hazards to some degree, indicating a discrepancy between what practitioners recognize as threats and the research that is being conducted. In sum, the literature is unbalanced in its treatment of water system impacts of wildfire. Water quality and water quantity impacts are well represented in the peer-reviewed literature, and research in these areas continues to grow. However, the impact on built water infrastructure and the interlinks and cascading effects of wildfire are far less frequently studied but more likely to be included in practitioner-oriented gray literature.

Eight key categories of wildfire-related hazards to water systems were identified through our systematic review (Fig. 2). These hazards are not evenly distributed over time and space and can arise sequentially or concurrently depending on the biogeophysical context and human response. While wildfire is a natural process necessary for resilient forested ecosystems in many landscapes, the expansive, high-severity, and high-intensity wildfires common in the 21st century often result in the loss of normal ecosystem functions, which are critical to maintaining and stabilizing water systems. These disruptions can precipitate a range of hazards that threaten water quality, quantity, and infrastructure including floods, landslides, and debris flows, decreased snowpack retention and early snowmelt, and surface and groundwater contamination. The volume of research exploring these post-fire impacts on water quality and quantity has grown substantially in recent years.

Wildfire impacts to water quality, quantity, and infrastructure

The growing body of research on water quality and water quantity impacts to wildfires has well characterized many of the main trends associated with wildfire burns. Wildfires can fundamentally change water quality by accelerating erosion and liberating constituents from organic materials, soils, and the built environment that are then readily delivered to surface waters via wet and dry depositional processes (*12*–*16*). Elevated concentrations of heavy metals, trace elements, nitrogen, phosphorus, and organic carbon are commonly detected in fire-affected watersheds [e.g., (*15*, *30*)]. In many contexts, the most severe declines in water quality correspond with the first post-fire flushes and high-intensity rainfall events [e.g. (*16*, *31*, *32*)]. Ash, sediment, and other contaminants accumulate on the soil surface during fires, and high levels of runoff produced during the first post-fire storms and snowmelt mobilize the constituents in substantial quantities, flushing them into surface waters (*33*, *34*).

Water quality recovery typically occurs within 2 to 3 years after fire, with the most severe impacts observed within the first year (*35*, *36*). However, even transient declines in water quality can present substantial water treatment challenges. Notably, delayed water quality recovery has been observed, sometimes attributed to post-fire drought (*37*–*40*). Changes in water quality are also leading to challenges in the treatment of drinking water (*41*). Many treatment facilities are not prepared to meet these challenges, which can (but not always) require additional processes, lead to increased costs, and may even result in supply disruption (*15*, *41*).

Wildfires typically also result in water quantity changes with temporarily increased runoff, streamflow, and flood risk. The loss of vegetation as a result of low- to high-severity wildfires leads to decreased evapotranspiration and interception [e.g., (*17*, *42*, *43*)]. Combined with fire-related soil water repellency, these factors have been found to result in considerable increases in overland flow and water yield, particularly during high-intensity rainfall events [e.g., (*17*, *42*, *44*–*47*)]. Wildfires may also lead to earlier and increased snowmelt as fire-related debris decreases albedo and the loss of forest canopy increases solar radiation reaching the snowpack (*48*–*52*). Typically, streamflow peaks in the first year following the fire but can remain elevated for many years [e.g., (*44*, *53*)].

Built water infrastructure ranging from treatment facilities and reservoirs to aboveground pipes and water meters may be directly

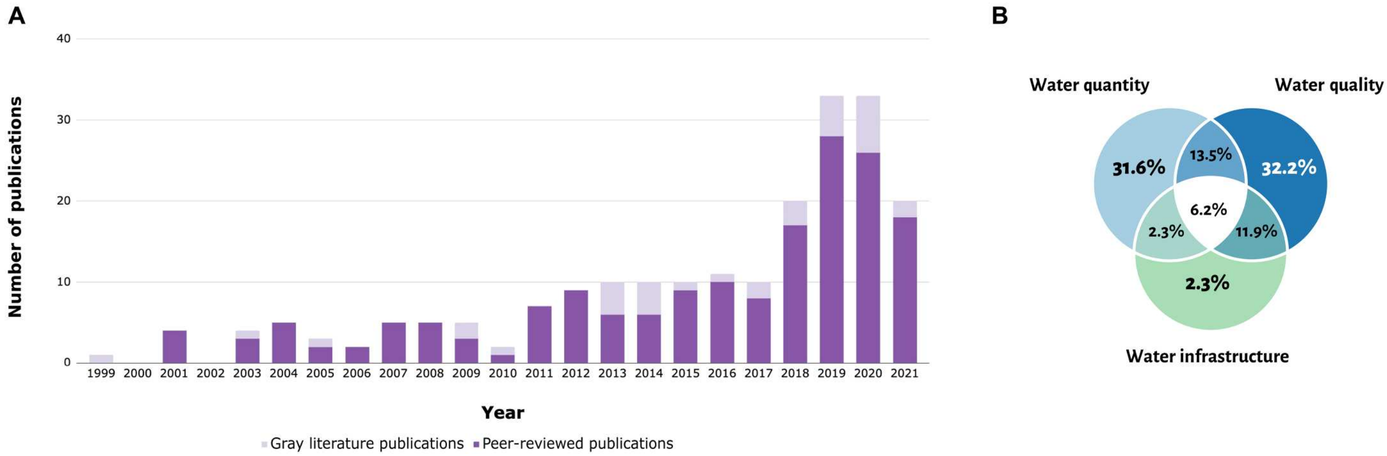

Fig. 1. The state of the peer-reviewed and gray literature assessing wildfire impacts to water systems over time and amongst water categories. The 212 peer-reviewed and gray literature items reviewed by publication year (**A**). The percentage of peer-reviewed publications represented by category (**B**). Publications in 2022 are not shown on the bar graph as papers were collected midway through the year.

damaged when exposed to flames and extreme temperatures associated with wildfire. Direct damage to water distribution systems, which can interrupt service and contaminate drinking water, threatens water utilities and their customers as wildfires increasingly occur within the WUI (*54*). Several recent studies have identified water contamination in and around burnt structures as a result of heat damage to plastic plumbing components as well as backflow of contaminated water and air into the water distribution system (*11*, *55*). Following California's Tubbs Fire of 2017 and Camp Fire of 2018, community-wide water supply disruptions occurred because of contamination from volatile organic compounds (*11*, *20*). The risk of these events will likely rise with the growing incidence of wildfire at the WUI (*11*, *20*), with cascading impacts to downstream communities. Built infrastructure may also suffer indirect damage as a result of secondary post-fire hazards such as flooding and debris flows. Reservoir sedimentation is a costly indirect consequence of wildfire that can result in interruptions to water supply (*10*, *56*, *57*).

Infrastructure provides the terminal connection in the path linking source water to community water users. Therefore, infrastructural vulnerabilities to the direct and indirect impact of wildfire may create a bottleneck constraining water availability and access. As mentioned in the previous section, this area has received less attention in the literature, and, thus, our understanding of this bottleneck is limited. The cumulative effects of multiple water quality and quantity hazards challenge the built capacity of many water systems.

Controls on wildfire water system impacts

The biogeophysical context of a region influences both its vulnerability to wildfire and its susceptibility to generating post-fire hazards to water. The interaction of climate patterns, topography, soil characteristics, vegetation regime, and hydrologic traits with fire severity, intensity, and extent determines impacts to water systems. For instance, regional climate patterns influence fire risk, the timing and duration of fire season, post-fire precipitation, the pace of vegetative recovery, and water availability. Topography affects post-fire erosion, landslide, and debris flow susceptibility as well as soil moisture and snowmelt dynamics. Soil properties influence post-fire infiltration and runoff processes, erodibility, and availability of constituents that may affect water chemistry. The vegetation regime also plays a considerable role in fire risk, severity, and recovery. Forest density, vegetation aridity, and fuel availability increase fire risk and severity (*3*, *26*, *58*). The accumulation of fuel loads and increased forest density and homogeneity due to legacy fire suppression regimes coupled with climate change have resulted in heightened fire risk across the western United States and elsewhere (*59*–*62*). Last, hydrologic traits such as peak flow, seasonality, and baseflow influence post-fire changes to streamflow, flood risk, and the magnitude of water quantity impacts. Wildfires damage soil and vegetation, deteriorating the hydrologic condition of watersheds, leading to elevated water yield and flood risk [e.g., (*44*, *63*, *64*)].

The coincidence of biogeophysical characteristics determines wildfire conditions, but, in turn, the direct and indirect impacts of wildfire may transform the biogeophysical characteristics of an affected area. post-fire erosion, landslides, and debris flows can alter topography [e.g., (*10*, *65*–*67*)]. Burning and high temperatures can destroy soil organic material, harm the soil microbiology, and lead to the formation of a soil water-repellent layer on the soil surface [e.g., (*13*, *68*)]. Fires may thin vegetation, promote the growth of fire-tolerant species, or otherwise permanently or temporarily alter the vegetation regime [e.g., (*17*, *69*)]. These effects, in turn, can alter the normal water balance leading to an increased and more variable water yield (*17*, *42*, *44*–*47*).

Wildfire severity, intensity, and extent control the degree of impact on local biogeophysical characteristics as well as the severity of post-fire water quality, quantity, and infrastructure hazards. Changes to water quantity and quality typically increase with burn severity and extent [for example, see (*65*, *66*)]. Low-severity fires, such as prescribed burns, typically do not produce harmful water quality, quantity, or infrastructure impacts (*64*, *70*), making a compelling case for active fire management. These fires can increase water yield but, unlike catastrophic wildfires, do so in a way that mimics natural processes (*64*, *71*). In contrast, areas burned at high severity typically experience more acute water hazards including debris flows and flooding [for example, see (*18*,

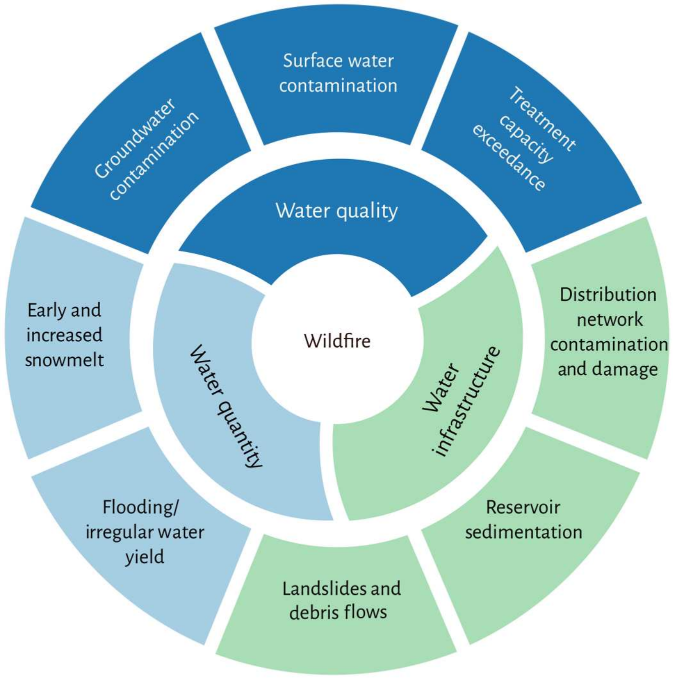

Fig. 2. Wildfires threaten water quality, quantity, and infrastructure. The outer ring of the figure depicts the eight key wildfire-induced hazards to water systems identified in this review.

72, *73*)]. Similarly, watersheds burned to a greater extent typically experience more severe water quality impairment, while the impacts are typically diluted in watersheds with limited burn area (*74*).

Table 1. Overview of approaches proposed in the reviewed literature to attenuate wildfire risks to water systems.

Actions to decrease vulnerability	References	Actions to increase resilience	References
Fuels reduction and thinning	(*23*, *26*, *97*)	Improved prediction and warning systems	(*63*)
Improved wildfire containment	(*98*)	Collaborative water management	(*92*)
Update building codes	(*11*, *95*)	Erosion control	(*80*, *95*)
Coupled wildfire and water risk assessments	(*99*)	Water treatability assessments	(*27*)
Afforestation with native species	(*46*)	Water infrastructure redundancies	(*90*)
Managed fire	(*100*)	Flexible water sourcing/diversion	(*23*)
Identify policy priorities	(*11*)	Safe disposal of damaged infrastructure and waste	(*101*)
		Forest restoration	(*69*)

post-fire hazards to water quality, quantity, and built infrastructure may occur days to years following the initial fire with consequences for water availability and access. As the threat of wildfire grows and evolves with climate change, so too will wildfire impacts to water availability and access [e.g., (*75*, *76*)]. However, much of our present understanding of these hazards remains fragmented as the current research on the wildfire water nexus often does not address the interactions between the three hazards as shown in Fig. 1.

Consequences of and opportunities for land use planning and management

Land use planning and management decisions both before and after a severe wildfire have multispatial and temporal impacts on water systems and wildfire risk, exposure, and recovery. Land use planning and forest management practices centered around fire suppression have contributed to the elevated fire risk in the western United States and across the globe [e.g., (*61*)]. Human encroachment into the WUI has further contributed to the rise in wildfire occurrence (*4*, *77*, *78*), which has also increased wildfire exposure for communities and infrastructure in the expanding WUI (*79*). The impacts of these land use planning and management trends on wildfire risk are further compounded by the effects of climate change (*4*). Given the current state of the literature, it is unclear if there has already been an increase in destructive impacts to water infrastructure systems, but the increase in large fire frequency in and near the WUI suggests that this is and will continue to occur. The key pre-fire mitigation and post-fire adaptation strategies to enhance water system resilience to fire hazards have been summarized in Table 1.

pre-fire management approaches to mitigating impacts to water systems have become increasingly important in recent years as fuel conditions have grown more hazardous. Fuel reductions (e.g., prescribed and cultural burns, managed wildfire, and mechanical thinning) are frequently the first line of defense against wildfire. Positioning infrastructure and creating defensible spaces to reduce exposure to future wildfires in addition to ensuring water infrastructure redundancies, flexible water sourcing and diversion, building code updates, and enhanced remote operation capabilities for water facilities are all management options to better insulate the water supply from post-fire disruptions.

Postwildfire management and adaptation actions to effectively respond to risks to both natural (e.g., watersheds) and built (e.g., pipes and reservoirs) water infrastructure can help ensure future water availability as wildfires give rise to increasing water supply disruptions. Unfortunately, few strategies currently exist to effectively mitigate post-fire water system hazards across large areas. Erosion control methods (e.g., hydromulching, reseeding, and debris dams) have been frequently deployed to mitigate water quality declines [e.g., (*80*, *81*)], but the implementation of these measures across extensive burn areas is often infeasible.

Last, it is important to acknowledge the human and institutional infrastructure required to support resilient water systems. Wildfire impacts to water systems intersect with multiple types of governing agencies, including those with land-use, fire, and water related authorities that span from local to national scales. In addition, community-based organizations and nongovernmental organizations can be very active in this space (*82*, *83*). Risk reduction strategies, such as prescribed burns, face multiple barriers to implementation from a sociopolitical perspective, including availability of financial and technical resources and stringent regulations for the practice (*84*). The ability of these entities to coordinate across scales for both risk reduction and post-fire response is an important factor in a region's ability to support wildfire-resilient water systems in a way that is just and equitable (*85*).

A holistic approach

Climate change is exacerbating the threat of severe wildfires and the ability of communities to access safe, affordable, and acceptable water for both potable and nonpotable uses—what we refer to here as water availability and access. Additional preparation is necessary to ensure that our critical water infrastructure can withstand the escalating hazards of wildfire events. This underpins the need for a holistic approach to better assessing aggregate risk and anticipate emerging post-fire impacts to water systems at multiple scales. Such an approach can enable a deeper understanding of the linkages between source water, wildfire, and infrastructure and inform effective and resilient management of water systems in the evolving context of wildfire and climate change.

While current research questions may blend water quality, quantity, and infrastructure concerns, the consideration of all three components concurrently is needed to develop a holistic approach to assessing post-fire risk to water systems. In pursuit of filling this gap, wildfire research should seek to enable a multidimensional understanding of wildfire risks to water systems. Interdisciplinary and transdisciplinary methods are well positioned to understand the effects of post-fire water quality, quantity, and infrastructure interactions. Research questions themselves need not be holistic to be useful but rather can work within a holistic systems perspective to fill identified gaps. This research can also further inform pre-fire mitigation strategies through feedback loops.

Here, we propose a holistic framework to assess interactions and feedback loops between water quality, quantity, and infrastructure as determinants of post-fire water availability and access (Fig. 3). These relationships are drawn from across the existing literature. This paper fills existing research gaps by offering a comprehensive and holistic view, summarizing our assessment of the linkages between wildfire and water availability.

Building on the literature reviewed above, in this framework, the biogeophysical characteristics of a watershed, specifically climate patterns, topography, soil characteristics, vegetation regime, and hydrologic traits, determine source water quality and quantity, as well as wildfire severity, intensity, and extent. In turn, the severity, extent, and intensity of wildfires generate hazards that directly and indirectly affect source water and infrastructure and, ultimately, water access and availability. Climate change acts on the biogeophysical and water supply systems, increasing risk and vulnerability to post-fire water hazards. However, land use planning (e.g., residential development, water treatment, distribution infrastructure, and roads) and management actions (e.g., forest management including thinning and prescribed fire and erosion control) to decrease vulnerability and increase resilience can alter the biogeophysical characteristics of watersheds and water supply systems to mitigate and adapt to these post-fire water hazards. However, some present management practices themselves, such as fire suppression, increase vulnerability and challenge resilience. Appropriate selection and implementation of management plans are essential for mitigating and adapting to the harmful effects of climate change. For example, selective tree thinning and prescribed burning in overgrown forests, as part of comprehensive forest management, can not only increase landscape resilience to drought but also increase streamflow in some geographies (*69*).

DISCUSSION

Supporting water system resilience requires connecting science to policy and decision-making through investment in data and information technology infrastructure. The extant literature is primarily concerned with identifying post-fire outcomes for fire-affected water systems. In contrast, less effort has been made to identify the mechanisms controlling the nature, timing, duration, severity, and spatial extent of these hazards nor the adverse outcomes they typically produce and possible risk reduction associated with various management strategies. Therefore, while we can glean general approaches to increasing system resilience, we struggle to link this research with effective management applications based on their unique connections to hydrologic processes.

For instance, it is well known that vegetative recovery is often an important precondition for post-fire hydrologic recovery, but the precise mechanisms by which revegetation prompts hydrologic recovery is not fully known. The role of root density, community structure, forest age, and other characteristics in the return to pre-fire hydrology is not well understood but could provide valuable insight into the pace of the post-fire recovery process. Knowledge of this kind as it relates to post-fire water hazards could play a role in informing the design of effective, holistic risk assessment and hazard mitigation strategies and policies. To clarify the linkages between wildfire, water quality, water quantity, and water infrastructure impacts, reliable long-term data availability, consistent metrics, greater research in shared contexts, more extensive research beyond the burn area, and multistakeholder collaboration are needed.

Baseline data availability is a perennial challenge of research, as well as decision-making, at the wildfire-water nexus

Many fire-prone regions lack long-term, continuous monitoring of water quality and quantity due to the cost and human resources required to install and operate in situ monitoring devices. Luckily, the advent of remote sensing has enabled better, cheaper, and more frequent measurements that can complement these on-the-ground readings, but many challenges remain. Inadequate availability of pre-fire baseline data for fire-affected watersheds presents a challenge for researchers, typically requiring them to identify similar, unaffected watersheds to act as controls and perform additional monitoring at those sites. Data-rich regions where managers and researchers have invested in monitoring infrastructure are overrepresented in the literature as the availability of long-term water quality and quantity data is a prerequisite for the before-after analysis of post-wildfire impacts. In addition, post-fire water monitoring is typically limited to 3 to 5 years. Limited long-term pre-fire and post-fire water quality and quantity monitoring limits our understanding of the post-fire recovery timeline across diverse climatic, ecological, and burn contexts.

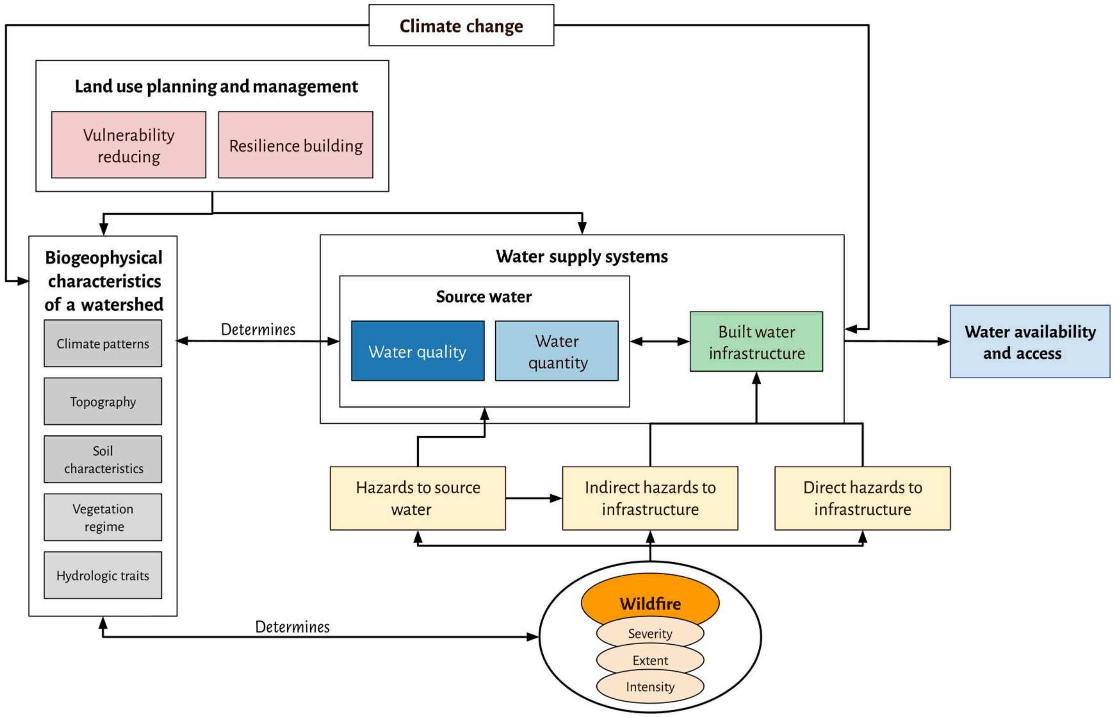

Fig. 3. A holistic framework representing water availability as a function of fire-affected water quality, quantity, and infrastructure interactions.

Inconsistent use of vegetative, hydrologic, and soil recovery metrics across publications challenges our understanding of postfire water systems recovery

The lack of uniformity in recovery indicators makes it difficult to identify the mechanisms guiding water system recovery and to compare findings across publications. Vegetative recovery, often measured through remote sensing methods, is frequently assessed with metrics including the normalized difference vegetation index and related geospatial indicators. However, changes in community structure and measures of diversity, richness, and/or evenness assessed from the ground are also used. Hydrologic recovery indicators used include the return to pre-fire streamflow, evapotranspiration, and water chemistry. Last, soil recovery has been identified by changes in soil hydraulic conductivity, structure, and other conditions, including the deterioration of the hydrophobic layer. Integrating, linking, and standardizing these multiple metrics could enhance our overall understanding and connect learnings across studies and regions.

Inadequate definitions and/or measurement approaches to classifying burn severity in the WUI

Remotely sensed Monitoring Trends in Burn Severity and Burn Area Reflectance Classification data dominate in the scientific literature, but these and other conventional burn severity definitions and datasets fail in WUI and urban geographies, which are increasingly consequential in research at the wildfire-water nexus. Burn severity data are most often derived from Monitoring Trends in Burn Severity for fire research in forested watersheds but are occasionally assessed on the basis of soil burn severity, loss of soil organic matter, or observations of visual indicators including canopy damage, root damage, debris consumed, and ash characteristics (*86*–*88*). However, research in the WUI demands unique measures of burn severity. For example, geospatial measures of burn severity that rely on changes in vegetation may be inaccurate for fires that affect built environments, such as those occurring at the WUI (*21*). Schulze and Fischer (*20*) use the density of damaged structures to measure burn severity following WUI fire, although opportunity remains to further develop approaches for WUI and urban contexts.

While WUI fires are increasing in occurrence, the majority of research is focused on undeveloped watersheds

Wildfire research must target all areas of risk, including WUI contexts, to support policy and decision-making. The watersheds that have received attention in the literature are often undeveloped headwaters that have typically burned at moderate to high severity across a large extent (>50%). While adverse impacts have been documented across low- to high-severity fires and small to large watersheds, some effects may be dampened at large spatial scales (*89*, *90*). Since watershed size likely influences the timing, duration, and severity of post-fire impacts on water systems, watersheds of varying scales may respond differently to management interventions. Thus, research at multiple spatial scales, burn severities, and levels of development is needed.

In addition, much of the reviewed literature evaluates the effects of wildfire on water quality and quantity within burned watersheds. However, the effects both upstream, because of aerial deposition, and downstream of the outlet in burned watersheds have received limited attention. A greater understanding of these system impacts that cascade into the WUI, particularly over time, is needed to identify the spatial and temporal risks for management planning purposes. Research on the WUI has grown substantially in recent years, but many challenges exist including data constraints due to privacy concerns, lack of baseline data given the continually changing rapid development, and challenge of methodological standardization in defining and studying the context (*4*, *91*).

Supporting resilience in the WUI requires greater collaboration between stakeholders and management communities

Often, watershed boundaries fall across multiple jurisdictions and property types, which presents a challenge for both pre-fire hazard mitigation and post-fire adaptation efforts (*69*, *92*). Across the literature, there is a recurring emphasis on the need for greater institutional coordination and clarification of responsibilities in hazard prevention and response. A shared understanding of the spatial and temporal distribution of post-fire water hazards can aid in these collaborative efforts by allowing communities to identify intertwined vulnerabilities and hazard mitigation opportunities. Improved collaboration allows for a quicker response to post-fire water hazards and contributes to greater trust in management agencies, which ultimately helps attenuate community vulnerability to post-fire water hazards (*24*, *26*, *92*, *93*).

In addition, water infrastructure vulnerability is closely intertwined with energy, transportation, and other critical infrastructure as wildfires may block or damage roads, inhibiting access to water treatment facilities or other infrastructure, and failure of the electrical grid may disrupt operations (*54*, *94*, *95*). Multistakeholder and utility coordination is critical to anticipating and responding to these hazards and funding pre-fire mitigation strategies. Understanding the local context and characteristics of WUI communities can help inform both their individual response to wildfires and how they can best collaborate with others (*96*). Further, more efficient modes of coordination between fire and water managers are needed to enhance mitigation and adaptation capacity.

Toward wildfire resilient water systems

The risk of wildfires to water availability and access across the world is growing rapidly, especially in arid and semiarid regions. In the face of these growing risks, the framework we present here for understanding the linkages between the biogeophysical context, wildfire, source water, and infrastructure, which shape water availability and access, can help resource managers and decision-makers build and maintain resilient water systems and communities. By adopting a holistic perspective on the interrelated effects of wildfires on water systems, decision-makers may better consider long- and short-term outcomes of management decisions, identify key intervention opportunities with the potential to generate multiple co-benefits across the system, and evaluate the tradeoffs between mitigation and adaptation management actions under different conditions.

To support efforts to plan for, mitigate, and respond to the evolving threat of wildfires to water systems, we need an interdisciplinary approach to research that explores the complex relationships shaping wildfire's threat to water availability and access. This is not to undermine the need for targeted research on specific impacts but rather emphasize that a holistic approach can build upon targeted research to identify and fill gaps in our knowledge

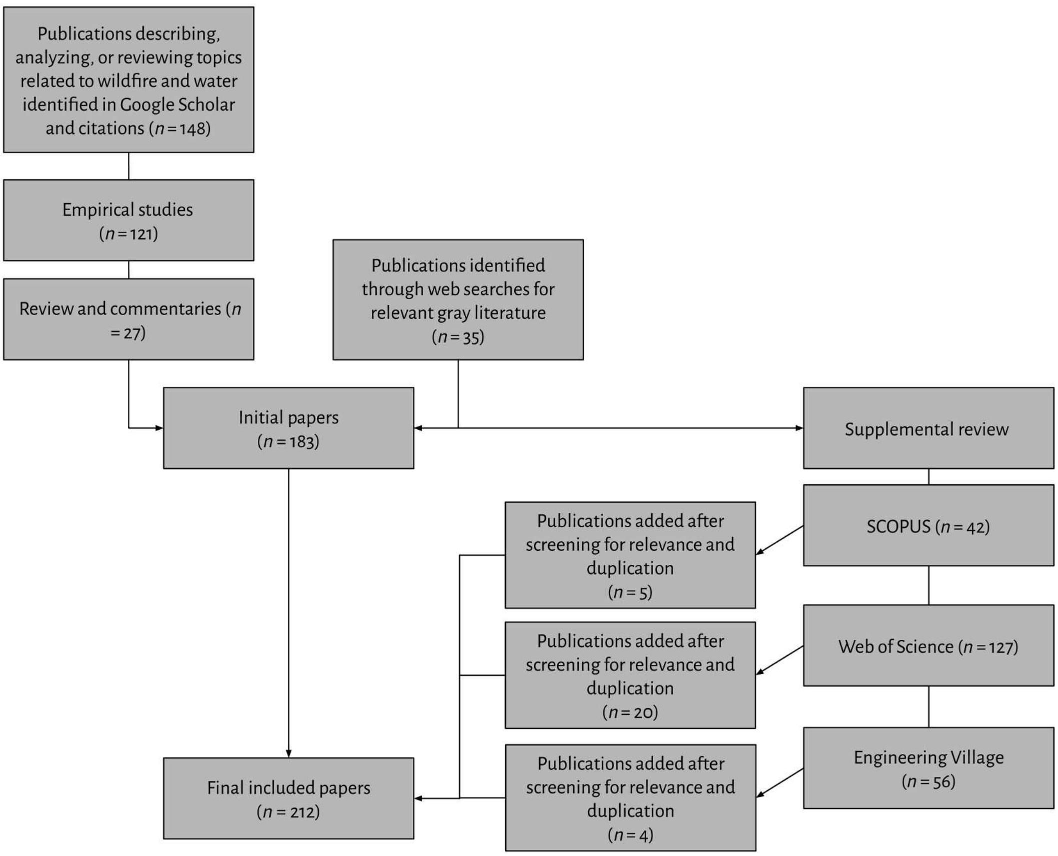

Fig. 4. Summary of the review process.

and management approaches. Greater collaboration is needed to reimagine wildfire and water research and better enable integrated knowledge and decision-making. Addressing the gaps in baseline data, uniform metrics, and WUI-specific studies is vital for supporting this interdisciplinary and convergence research. Of particular need is research into the social and distributional impact of post-fire water hazards. This knowledge will directly inform risk assessments for fire-vulnerable communities, which are largely disadvantaged and rural populations. Further, there is an opportunity for policy improvements to promote wildfire resilience of natural and built water infrastructure, but additional investigation is needed to identify the most salient needs.

MATERIALS AND METHODS

Experimental design

We reviewed 212 items from the English-language peer-reviewed (177 publications) and gray literature (35 publications) (Fig. 4). For the full list of publications reviewed, see data S1. Initially, we identified publications from paper citations and keyword searches in Google Scholar that included at least one wildfire-related and water-related term in each search. Wildfire related terms included "wildfire," "wildland-urban interface," and "post-fire" and water-related terms included "water," "water quality," "water quantity," "infrastructure," "hydrology," and "water yield." Several searches were also conducted including the names of severe wildfires in the western United States (i.e., Tubbs, Camp, Cerro Grande, and Carr Fires) with known water impacts. We did not define specific geographical inclusion criteria and accepted global publications; however, with the inclusion of specific fire search terms and focus on English-language literature, our review is skewed toward studies based in the western United States.

We included studies that either (i) tested empirically the relationship between wildfires and some dimension of water impacts (e.g., water quality, water quantity, or water infrastructure), (ii) reviewed literature that empirically tested the relationship between wildfires and one or more dimensions of water impacts, (iii) described theoretical models for understanding wildfire impacts to water systems, or (iv) described, analyzed, or prescribed practitioner approaches to mitigating wildfire impacts to water systems or increase the resilience of water systems to wildfire. We excluded papers that did not methodically examine water impacts for wildfires, such as those that identified water impacts as a post-fire concern but did not address them as a primary focus of the study. Empirical studies, meta-analyses, reviews, case studies, and commentaries were all accepted on the basis of our inclusion criteria. Ultimately, this process resulted in the identification of 184 papers. To supplement this narrative review, a series of systematic database searches were conducted in Web of Science, SCOPUS, and Engineering Village. These searches included two or more of the following terms, always with a combination of wildfire and water-related terms: "wildfire," "water," "*wildfire," "water*," {wildland urban interface}, {reservoir sedimentation}, and {water systems}. These searches resulted in the addition of 29 relevant publications to the review.

Supplementary Materials

This PDF file includes:
Tables S1 and S2
Legend for data S1
References

Other Supplementary Material for this manuscript includes the following:
Data S1

REFERENCES AND NOTES

1. P. E. Dennison, S. C. Brewer, J. D. Arnold, M. A. Moritz, Large wildfire trends in the western United States, 1984–2011. *Geophys. Res. Lett.* **41**, 2928–2933 (2014).
2. Z. Liu, M. C. Wimberly, A. Lamsal, T. L. Sohl, T. J. Hawbaker, Climate change and wildfire risk in an expanding wildland-urban interface: A case study from the Colorado front range corridor. *Landsc. Ecol.* **30**, 1943–1957 (2015).
3. J. T. Abatzoglou, A. P. Williams, Impact of anthropogenic climate change on wildfire across western US forests. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 11770–11775 (2016).
4. V. C. Radeloff, D. P. Helmers, H. A. Kramer, M. H. Mockrin, P. M. Alexandre, A. Bar-Massada, V. Butsic, T. J. Hawbaker, S. Martinuzzi, A. D. Syphard, S. I. Stewart, Rapid growth of the US wildland-urban interface raises wildfire risk. *PNAS* **115**, 3314–3319 (2018).
5. C. S. Stevens-Rumann, K. B. Kemp, P. E. Higuera, B. J. Harvey, M. T. Rother, D. C. Donato, P. Morgan, T. T. Veblen, Evidence for declining forest resilience to wildfires under climate change. *Ecol. Lett.* **21**, 243–252 (2018).
6. M. Goss, D. L. Swain, J. T. Abatzoglou, A. Sarhadi, C. A. Kolden, A. P. Williams, N. S. Diffenbaugh, Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environ. Res. Lett.* **15**, 094016 (2020).
7. N. Liu, G. R. Dobbs, P. V. Caldwell, C. F. Miniat, G. Sun, K. Duan, S. A. C. Nelson, P. V. Bolstad, C. P. Carlson, Inter-basin transfers extend the benefits of water from forests to population centers across the conterminous U.S. *Water Resour. Res.* **58**, e2021WR031537 (2022).
8. N. Liu, P. V. Caldwell, G. R. Dobbs, C. F. Miniat, P. V. Bolstad, S. A. C. Nelson, G. Sun, Forested lands dominate drinking water supply in the conterminous United States. *Environ. Res. Lett.* **16**, 084008 (2021).
9. E. Weidner, A. Todd, "From the forest to the faucet drinking water and forests in the US" (USDA Forest Service, 2011).
10. A. E. East, J. B. Logan, P. Dartnell, O. Lieber-Kotz, D. B. Cavagnaro, S. W. McCoy, D. N. Lindsay, Watershed sediment yield following the 2018 Carr Fire, Whiskeytown National Recreation Area, northern California. *Earth Sp. Sci.* **8**, 10.1029/2021EA001828, (2021).
11. C. R. Proctor, J. Lee, D. Yu, A. D. Shah, A. J. Whelton, Wildfire caused widespread drinking water distribution network contamination. *AWWA Water Sci.* **2**, e1183 (2020).
12. R. L. Kelly, X. Bian, S. J. Feakins, K. L. Fornace, T. Gunderson, N. J. Hawco, H. Liang, J. Niggemann, S. E. Paulson, P. Pinedo-Gonzalez, A. J. West, S. Yang, S. G. John, Delivery of metals and dissolved black carbon to the Southern California coastal ocean via aerosols and floodwaters following the 2017 Thomas fire. *J. Geophys. Res. Biogeo.* **126**, e2020JG006117 (2021).
13. D. G. Neary, K. C. Ryan, L. F. DeBano, "Wildland fire in ecosystems: Effects of fire on soils and water" (Gen. Tech. Rep. RMRS-GRT-42-vol.4, USDA Forest Service, 2005).
14. F. Scordo, S. Chandra, E. Suenaga, S. J. Kelson, J. Culpepper, L. Scaff, F. Tromboni, T. J. Caldwell, C. Seitz, J. E. Fiorenza, C. E. Williamson, S. Sadro, K. C. Rose, S. R. Poulson, Smoke from regional wildfires alters lake ecology. *Sci. Rep.* **11**, 10922 (2021).
15. H. G. Smith, G. J. Sheridan, P. N. J. Lane, P. Nyman, S. Haydon, Wildfire effects on water quality in forest catchments: A review with implications for water supply. *J. Hydrol.* **396**, 170–192 (2011).
16. E. D. Stein, J. S. Brown, T. S. Hogue, M. P. Burke, A. Kinoshita, Stormwater contaminant loading following southern California wildfires. *Environ. Toxicol. Chem.* **31**, 2625–2638 (2012).
17. K. Blount, C. J. Ruybal, K. J. Franz, T. S. Hogue, Increased water yield and altered water partitioning follow wildfire in a forested catchment in the western United States. *Ecohydrology.* **13**, e2170 (2020).
18. H. A. Moreno, J. J. Gourley, T. G. Pham, D. M. Spade, Utility of satellite-derived burn severity to study short- and long-term effects of wildfire on streamflow at the basin scale. *J. Hydrol.* **580**, 124244 (2020).
19. M. L. Wine, D. Cadol, Hydrologic effects of large southwestern USA wildfires significantly increase regional water supply: Fact or fiction? *Environ. Res. Lett.* **11**, 085006 (2016).

20. S. S. Schulze, E. C. Fischer, Prediction of water distribution system contamination based on wildfire burn severity in wildland urban interface communities. *ACS ES&T Water.* **1**, 291–299 (2021).
21. S. Reardon, "'Burn Scars' of wildfires threaten drinking water in California and the West," *Los Angeles Times*, 27 September 2021; https://www.latimes.com/environment/story/2021-09-27/burn-scars-of-wildfires-threaten-drinking-water-across-much-of-the-west.
22. L. Madeira, T. Gartner, Forest resilience bond sparks innovative collaborations between water utilities and wide-ranging stakeholders. *J. Am. Water Works Assoc.* **110**, 42–49 (2018).
23. C. H. Sham, M. E. Tuccillo, J. Rooke, "Effects of wildfire on drinking water utilities and best practices for wildfire risk reduction and mitigation" (EPA Web Report #4482, Water Research Foundation, 2013).
24. S. Ozment, T. Gartner, H. Huber-Stearns, K. DiFrancesco, N. Lichten, S. Tognetti, "Protecting drinking water at the source" (World Resources Institute, 2016); www.wri.org/publication/protecting-drinking-water-source.
25. E. Margolis, M. Savage, L. A. W. Plan, D. Lyons, S. Fe, W. Division, O. Plan, E. Everett, "Santa Fe municipal watershed plan, 2010–2029" (2013); https://santafenm.gov/document_center/document/780.
26. The Nature Conservancy, "Rio Grande water fund comprehensive plan for wildfire and water source protection, 1–44" (2014); https://riograndewaterfund.org/wp-content/uploads/2017/01/rgwf_compplan.pdf).
27. M. B. Emelko, U. Silins, K. D. Bladon, M. Stone, Implications of land disturbance on drinking water treatability in a changing climate: Demonstrating the need for "source water supply and protection" strategies. *Water Res.* **45**, 461–472 (2011).
28. S. M. Stein, M. A. Carr, S. J. Comas, S. I. Stewart, H. Cleveland, L. Bramwell, V. C. Radeloff, "Wildfire, wildlands, and people: Understanding and preparing for wildfire in the wildland-urban interface" (Gen. Tech. Rep. RMRS-GTR-299, USDA Forest Service, 2013).
29. N. I. F. Center, "Fire information statistics" (National Interagency Fire Center, 2023); www.nifc.gov/fire-information/statistics.
30. J. Abraham, K. Dowling, S. Florentine, Risk of post-fire metal mobilization into surface water resources: A review. *Sci. Total Environ.* **599-600**, 1740–1755 (2017).
31. S. F. Murphy, J. H. Writer, R. B. McCleskey, D. A. Martin, The role of precipitation type, intensity, and spatial distribution in source water quality after wildfire. *Environ. Res. Lett.* **10**, 084007 (2015).
32. A. J. Rust, T. S. Hogue, S. Saxe, J. McCray, Post-fire water-quality response in the western United States. *Int. J. Wildl. Fire.* **27**, 203–216 (2018).
33. J. H. Writer, S. F. Murphy, "Wildfire effects on source-water quality-lessons from Fourmile Canyon Fire, Colorado, and implications for drinking-water treatment study rationale and approach" (Fact Sheet 2012-3095, USGS, 2012).
34. A. Tecle, D. Neary, Water quality impacts of forest fires. *J. Pollut. Eff. Control.* **3**, 140 (2015).
35. K. D. Bladon, U. Silins, M. J. Wagner, M. Stone, M. B. Emelko, C. A. Mendoza, K. J. Devito, S. Boon, Wildfire impacts on nitrogen concentration and production from headwater streams in Southern Alberta's rocky mountains. *Can. J. For. Res.* **38**, 2359–2371 (2008).
36. S. L. Rathburn, S. M. Shahverdian, S. E. Ryan, Post-disturbance sediment recovery: Implications for watershed resilience. *Geomorphology* **305**, 61–75 (2018).
37. A. T. Chow, K.-P. Tsai, T. S. Fegel, D. N. Pierson, C. C. Rhoades, Lasting effects of wildfire on disinfection by-product formation in forest catchments. *J. Environ. Qual.* **48**, 1826–1834 (2019).
38. M. Yu, T. F. A. Bishop, F. F. Van Ogtrop, Assessment of the decadal impact of wildfire on water quality in forested catchments. *Water.* **11**, 533 (2019).
39. C. C. Rhoades, A. T. Chow, T. P. Covino, T. S. Fegel, D. N. Pierson, A. E. Rhea, The legacy of a severe wildfire on stream nitrogen and carbon in headwater catchments. *Ecosystems* **22**, 643–657 (2019).
40. J. L. Florsheim, A. Chin, A. M. Kinoshita, S. Nourbakhshbeidokhti, Effect of storms during drought on post-wildfire recovery of channel sediment dynamics and habitat in the Southern California Chaparral, USA. *Earth Surf. Process. Landforms.* **42**, 1482–1492 (2017).
41. A. K. Hohner, K. Cawley, J. Oropeza, R. S. Summers, F. L. Rosario-Ortiz, Drinking water treatment response following a Colorado wildfire. *Water Res.* **105**, 187–198 (2016).
42. F. Z. Maina, E. R. Siirila-Woodburn, Watersheds dynamics following wildfires: Nonlinear feedbacks and implications on hydrologic responses. *Hydrol. Process.* **34**, 33–50 (2020).
43. P. K. Poon, A. M. Kinoshita, Spatial and temporal evapotranspiration trends after wildfire in semi-arid landscapes. *J. Hydrol.* **559**, 71–83 (2018).
44. R. R. Bart, A regional estimate of postfire streamflow change in California. *Water Resour. Res.* **52**, 1465–1478 (2016).
45. A. M. Kinoshita, T. S. Hogue, Increased dry season water yield in burned watersheds in Southern California. *Environ. Res. Lett.* **10**, 14003 (2015).
46. N. Ohana-Levi, A. Givati, T. Paz-Kagan, A. Karnieli, Forest composition effect on wildfire pattern and run-off regime in a Mediterranean watershed. *Ecohydrology* **11**, e1936 (2018).
47. M. L. Wine, D. Cadol, O. Makhnin, In ecoregions across western USA streamflow increases during post-wildfire recovery. *Environ. Res. Lett.* **13**, 14010 (2017).
48. K. Burles, S. Boon, Snowmelt energy balance in a burned forest plot, Crowsnest Pass, Alberta, Canada. *Hydrol. Process.* **25**, 3012–3029 (2011).
49. K. E. Gleason, A. W. Nolin, T. R. Roth, Charred forests increase snowmelt: Effects of burned woody debris and incoming solar radiation on snow ablation. *Geophys. Res. Lett.* **40**, 4654–4661 (2013).
50. P. D. Micheletty, A. M. Kinoshita, T. S. Hogue, Application of MODIS snow cover products: Wildfire impacts on snow and melt in the Sierra Nevada. *Hydrol. Earth Syst. Sci.* **18**, 4601–4615 (2014).
51. J. D. Maxwell, A. Call, S. B. St, Wildfire and topography impacts on snow accumulation and retention in montane forests. *For. Ecol. Manage.* **432**, 256–263 (2019).
52. T. M. Uecker, S. D. Kaspari, K. N. Musselman, S. M. Skiles, The post-wildfire impact of burn severity and age on black carbon snow deposition and implications for snow water resources, cascade range, Washington. *J. Hydrometeorol.* **21**, 1777–1792 (2020).
53. S. Saxe, T. S. Hogue, L. Hay, Characterization and evaluation of controls on post-fire streamflow response across western US watersheds. *Hydrol. Earth Syst. Sci.* **22**, 1221–1237 (2018).
54. A. J. Whelton, C. Seidel, B. P. Wham, E. C. Fischer, K. Isaacson, C. Jankowski, N. MacArthur, E. McKenna, C. Ley, The Marshall fire: Scientific and policy needs for water system disaster response. *AWWA Water Sci.* **5**, e1318 (2023).
55. G. M. Solomon, S. Hurley, C. Carpenter, T. M. Young, P. English, P. Reynolds, Fire and water: Assessing drinking water contamination after a major wildfire. *ACS ES&T Water.* **1**, 1878–1886 (2021).
56. J. A. Moody, D. a. Martin, Wildfire impacts on reservoir sedimentation in the western United States, in *The Ninth International Symposium on River Sedimentation, 1095–1102* (Tsinghua Univ. Press, 2004), pp. 1095–1102.
57. P. Nyman, P. Yeates, C. Langhans, P. Noske, S. Haydon, G. Sheridan, "Probability and consequence of post-fire contamination events in a water supply catchment" (Australian Institute for Disaster Resilience, 2019); www.bnhcrc.com.au/sites/default/files/managed/downloads/peter_nyman.pdf.
58. C. H. S. Williams, U. Silins, S. A. Spencer, M. J. Wagner, M. Stone, M. B. Emelko, C. H. S. Williams, U. Silins, S. A. Spencer, M. J. Wagner, M. Stone, M. B. Emelko, Net precipitation in burned and unburned subalpine forest stands after wildfire in the northern Rocky Mountains. *Int. J. Wildl. Fire* **28**, 750–760 (2019).
59. A. E. Scholl, A. H. Taylor, Fire regimes, forest change, and self-organization in an old-growth mixed-conifer forest, Yosemite National Park, USA. *Ecol. Appl.* **20**, 362–380 (2010).
60. B. M. Collins, R. G. Everett, S. L. Stephens, Impacts of fire exclusion and recent managed fire on forest structure in old growth Sierra Nevada mixed-conifer forests. *Ecosphere* **2**, art51 (2011).
61. S. A. Parks, C. Miller, M. A. Parisien, L. M. Holsinger, S. Z. Dobrowski, J. Abatzoglou, Wildland fire deficit and surplus in the western United States, 1984-2012. *Ecosphere* **6**, 1–13 (2015).
62. H. Mccann, V. Butsic, J. Battles, R. Cisneros, Y. Jin, S. Kocher, M. D. Potts, S. Stephens, C. Herbert, S. Smith, "The benefits of headwater forest management" (Public Policy Institute of California, 2020); www.ppic.org/wp-content/uploads/the-benefits-of-headwater-forest-management-april-2020.pdf.
63. S. H. Cannon, J. E. Gartner, R. C. Wilson, J. C. Bowers, J. L. Laber, Storm rainfall conditions for floods and debris flows from recently burned areas in Southwestern Colorado and Southern California. *Geomorphology* **96**, 250–269 (2008).
64. D. W. Hallema, G. Sun, P. V. Caldwell, F. Robinne, K. D. Bladon, S. P. Norman, Y. Liu, E. C. Cohen, S. G. McNulty, "Wildland fire impacts on water yield across the contiguous United States" (Gen. Tech. Rep. SRS-238, USDA Forest Service, 2019); www.fs.usda.gov/research/treesearch/58095.
65. J. A. Moody, R. A. Shakesby, P. R. Robichaud, S. H. Cannon, D. A. Martin, Current research issues related to post-wildfire runoff and erosion processes. *Earth Sci. Rev.* **122**, 10–37 (2013).
66. R. B. Abney, T. J. Kuhn, A. Chow, W. Hockaday, M. L. Fogel, A. A. Berhe, Pyrogenic carbon erosion after the Rim Fire, Yosemite National Park: The role of burn severity and slope. *J. Geophys. Res. Biogeo.* **124**, 432–449 (2019).
67. F. K. Rengers, L. A. McGuire, N. S. Oakley, J. W. Kean, D. M. Staley, H. Tang, Landslides after wildfire: Initiation, magnitude, and mobility. *Landslides* **17**, 2631–2641 (2020).
68. G. G. Ice, D. G. Neary, P. W. Adams, Effects of wildfire on soils and watershed processes. *J. For.* **102**, 16–20 (2004).
69. Q. Ma, R. C. Bales, J. Rungee, M. H. Conklin, B. M. Collins, M. L. Goulden, Wildfire controls on evapotranspiration in California's Sierra Nevada. *J. Hydrol.* **590**, 125364 (2020).
70. D. W. Hallema, G. Sun, P. V. Caldwell, S. P. Norman, E. C. Cohen, Y. Liu, K. D. Bladon, S. G. McNulty, Burned forests impact water supplies. *Nat. Commun.* **9**, 1–8 (2018).

71. D. W. Hallema, G. Sun, K. D. Bladon, S. P. Norman, P. V. Caldwell, Y. Liu, S. G. McNulty, Regional patterns of postwildfire streamflow response in the Western United States: The importance of scale-specific connectivity. *Hydrol. Process.* **31**, 2582–2598 (2017).
72. P. Nyman, H. G. Smith, C. B. Sherwin, C. Langhans, P. N. J. Lane, G. J. Sheridan, Predicting sediment delivery from debris flows after wildfire. *Geomorphology* **250**, 173–186 (2015).
73. F. K. Rengers, L. A. McGuire, J. W. Kean, D. M. Staley, A. M. Youberg, Progress in simplifying hydrologic model parameterization for broad applications to post-wildfire flooding and debris-flow hazards. *Earth Surf. Process. Landforms* **44**, 3078–3092 (2019).
74. C. A. Emmerton, C. A. Cooke, S. Hustins, U. Silins, M. B. Emelko, T. Lewis, M. K. Kruk, N. Taube, D. Zhu, B. Jackson, M. Stone, J. G. Kerr, J. F. Orwin, Severe Western Canadian wildfire affects water quality even at large basin scales. *Water Res.* **183**, 116071 (2020).
75. D. Touma, S. Stevenson, D. L. Swain, D. Singh, D. A. Kalashnikov, X. Huang, Climate change increases risk of extreme rainfall following wildfire in the Western United States. *Sci. Adv.* **8**, eabm0320 (2022).
76. J. B. Sankey, J. Kreitler, T. J. Hawbaker, J. L. McVay, M. E. Miller, E. R. Mueller, N. M. Vaillant, S. E. Lowe, T. T. Sankey, Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds. *Geophys. Res. Lett.* **44**, 8884–8892 (2017).
77. D. M. Theobald, W. H. Romme, Expansion of the US wildland-urban interface. *Landsc. Urban Plan.* **83**, 340–354 (2007).
78. H. A. Kramer, M. H. Mockrin, P. M. Alexandre, V. C. Radeloff, High wildfire damage in interface communities in California. *Int. J. Wildl. Fire* **28**, 641 (2019).
79. A. A. Ager, P. Palaiologou, C. R. Evers, M. A. Day, C. Ringo, K. Short, Wildfire exposure to the wildland urban interface in the western US. *Appl. Geogr.* **111**, 102059 (2019).
80. D. N. Pierson, P. R. Robichaud, C. C. Rhoades, R. E. Brown, Soil carbon and nitrogen eroded after severe wildfire and erosion mitigation treatments. *Int. J. Wildl. Fire* **28**, 814 (2019).
81. D. A. Zema, Postfire management impacts on soil hydrology. *Curr. Opin. Environ. Sci. Heal.* **21**, 100252 (2021).
82. J. B. Abrams, M. Knapp, T. B. Paveglio, A. Ellison, C. Moseley, M. Nielsen-Pincus, M. S. Carroll, Re-envisioning community-wildfire relations in the U.S. West as adaptive governance. *Ecol. Soc.* **20**, (2015).
83. R. K. Miller, K. J. Mach, R. K. Miller, K. J. Mach, Roles and experiences of non-governmental organisations in wildfire response and recovery. *Int. J. Wildl. Fire.* **31**, 46–55 (2022).
84. R. K. Miller, C. B. Field, K. J. Mach, Barriers and enablers for prescribed burns for wildfire management in California. *Nat. Sustain.* **3**, 101–109 (2020).
85. M. R. Auer, Considering equity in wildfire protection. *Sustain. Sci.* **16**, 2163–2169 (2021).
86. M. P. Burke, T. S. Hogue, M. Ferreira, C. B. Mendez, B. Navarro, S. Lopez, J. A. Jay, The effect of wildfire on soil mercury concentrations in Southern California watersheds. *Water Air Soil Pollut.* **212**, 369–385 (2010).
87. H. Uzun, R. A. Dahlgren, C. Olivares, C. U. Erdem, T. Karanfil, A. T. Chow, Two years of post-wildfire impacts on dissolved organic matter, nitrogen, and precursors of disinfection by-products in California stream waters. *Water Res.* **181**, 115891 (2020).
88. J.-J. Wang, R. A. Dahlgren, M. S. Erşan, T. Karanfil, A. T. Chow, Wildfire altering terrestrial precursors of disinfection byproducts in forest detritus. *Environ. Sci. Technol.* **49**, 5921–5929 (2015).
89. F. N. Robinne, K. D. Bladon, U. Silins, M. B. Emelko, M. D. Flannigan, M. A. Parisien, X. Wang, S. W. Kienzle, D. P. Dupont, A regional-scale index for assessing the exposure of drinking-water sources to wildfires. *Forests* **10**, 384 (2019).
90. B. M. Gannon, Y. Wei, M. P. Thompson, J. H. Scott, K. C. Short, System analysis of wildfire-water supply risk in Colorado, USA with Monte Carlo wildfire and rainfall simulation. *Risk Anal.* **42**, 406–424 (2022).
91. A. Bento-Gonçalves, A. Vieira, Wildfires in the wildland-urban interface: Key concepts and evaluation methodologies. *Sci. Total Environ.* **707**, 135592 (2020).
92. K. Blount, A. Kroepsch, Improving the resilience of water resources after wildfire through collaborative watershed management: A case study from Colorado. *Case Stud. Environ.* **3**, 1–11 (2019).
93. T. O. Odimayomi, C. R. Proctor, Q. E. Wang, A. Sabbaghi, K. S. Peterson, D. J. Yu, J. Lee, A. D. Shah, C. J. Ley, Y. Noh, C. D. Smith, J. P. Webster, K. Milinkevich, M. W. Lodewyk, J. A. Jenks, J. F. Smith, A. J. Whelton, Water safety attitudes, risk perception, experiences, and education for households impacted by the 2018 Camp Fire, California. *Nat. Hazards.* **108**, 947–975 (2021).
94. J. Abelson, E. Bishop, D. Bruno, G. Bundesen, D. Constable, D. Cordell, A. Garcia, J. Gee, C. Harris, J. Hart, L. Johnson, K. Kasberg, M. Maurino, D. Mcpherson, M. Mouawad, T. Paul, G. Persad, A. Renteria, I. Ridderbusch, G. Sencan, M. Sparks-Kranz, S. Sugar, A. Zimmer, "Fire and water: An emerging nexus in California" (2019); https://www.watereducation.org/sites/main/files/file-attachments/water_leaders_final_report.pdf?1575675022.
95. A. Canning, G. Ryan, "Bushfire management: National good practice operational guidelines for the Australian water industry" (Water Services Association of Australia, 2020).
96. T. B. Paveglio, C. Moseley, M. S. Carroll, D. R. Williams, E. J. Davis, A. P. Fischer, Categorizing the social context of the wildland urban interface: Adaptive capacity for wildfire and community "archetypes". *For. Sci.* **61**, 298–310 (2015).
97. B. M. Gannon, Y. Wei, L. H. MacDonald, S. K. Kampf, K. W. Jones, J. B. Cannon, B. H. Wolk, A. S. Cheng, R. N. Addington, M. P. Thompson, B. M. Gannon, Y. Wei, L. H. MacDonald, S. K. Kampf, K. W. Jones, J. B. Cannon, B. H. Wolk, A. S. Cheng, R. N. Addington, M. P. Thompson, Prioritising fuels reduction for water supply protection. *Int. J. Wildl. Fire.* **28**, 785–803 (2019).
98. B. M. Gannon, Y. Wei, M. P. Thompson, Mitigating source water risks with improved wildfire containment. *Fire* **3**, 45 (2020).
99. D. W. Hallema, F. N. Robinne, K. D. Bladon, Reframing the challenge of global wildfire threats to water supplies. *Earth's Futur.* **6**, 772–776 (2018).
100. G. Boisramé, S. Thompson, S. Stephens, Hydrologic responses to restored wildfire regimes revealed by soil moisture-vegetation relationships. *Adv. Water Resour.* **112**, 124–146 (2018).
101. L. A. L. Hill, R. Blyth, E. M. Krieger, A. Smith, A. McPhail, S. B. C. Shonkoff, "The public health dimensions of California wildfire and wildfire prevention, mitigation and suppression" (Physicians, Scientists, and Engineers for Healthy Energy, 2020).
102. K. Cydzik, T. S. Hogue, Modeling postfire response and recovery using the hydrologic engineering center hydrologic modeling system (HEC-HMS). *JAWRA J. Am. Water Resour. Assoc.* **45**, 702–714 (2009).
103. H. Y. Jung, T. S. Hogue, L. K. Rademacher, T. Meixner, Impact of wildfire on source water contributions in Devil Creek, CA: Evidence from end-member mixing analysis. *Hydrol. Process.* **23**, 183–200 (2009).
104. A. M. Kinoshita, T. S. Hogue, Spatial and temporal controls on post-fire hydrologic recovery in Southern California watersheds. *Catena* **87**, 240–252 (2011).
105. D. M. Staley, J. A. Negri, J. W. Kean, J. L. Laber, A. C. Tillery, A. M. Youberg, Prediction of spatially explicit rainfall intensity–duration thresholds for post-fire debris-flow generation in the western United States. *Geomorphology* **278**, 149–162 (2017).
106. L. E. Flint, E. C. Underwood, A. L. Flint, A. D. Hollander, Characterizing the influence of fire on hydrology in Southern California. *Nat. Areas J.* **39**, 108–121 (2019).
107. P. M. Santi, B. Macaulay, Water and sediment supply requirements for post-wildfire debris flows in the Western United States. *Environ. Eng. Geosci.* **27**, 73–85 (2021).
108. B. A. Wilder, J. T. Lancaster, P. H. Cafferata, D. B. R. Coe, B. J. Swanson, D. N. Lindsay, W. R. Short, A. M. Kinoshita, An analytical solution for rapidly predicting post-fire peak streamflow for small watersheds in southern California. *Hydrol. Process.* **35**, e13976 (2021).
109. J. W. Kean, D. M. Staley, S. H. Cannon, In situ measurements of post-fire debris flows in southern California: Comparisons of the timing and magnitude of 24 debris-flow events with rainfall and soil moisture conditions. *Case Rep. Med.* **116**, 4019 (2011).
110. M. P. Burke, T. S. Hogue, A. M. Kinoshita, J. Barco, C. Wessel, E. D. Stein, Pre- and post-fire pollutant loads in an urban fringe watershed in Southern California. *Environ. Monit. Assess.* **185**, 10131–10145 (2013).
111. D. M. Staley, J. W. Kean, S. H. Cannon, K. M. Schmidt, J. L. Laber, Objective definition of rainfall intensity-duration thresholds for the initiation of post-fire debris flows in southern California. *Landslides* **10**, 547–562 (2013).
112. C. A. Burton, T. M. Hoefen, G. S. Plumlee, K. L. Baumberger, A. R. Backlin, E. Gallegos, R. N. Fisher, Trace elements in stormflow, ash, and burned soil following the 2009 station fire in Southern California. *PLOS ONE* **11**, e0153372 (2016).
113. F. K. Rengers, L. A. McGuire, J. W. Kean, D. M. Staley, D. E. J. Hobley, Model simulations of flood and debris flow timing in steep catchments after wildfire. *Water Resour. Res.* **52**, 6041–6061 (2016).
114. B. A. Ebel, E. S. Hinckley, D. A. Martin, Soil-water dynamics and unsaturated storage during snowmelt following wildfire. *Hydrol. Earth Syst. Sci.* **16**, 1401–1417 (2012).
115. B. A. Ebel, J. A. Moody, D. A. Martin, Hydrologic conditions controlling runoff generation immediately after wildfire. *Water Resour. Res.* **48**, 3529 (2012).
116. S. F. Murphy, R. Blaine McCleskey, J. H. Writer, Effects of flow regime on stream turbidity and suspended solids after wildfire, Colorado front range. *IAHS-AISH Publ.* **354**, 11–14 (2012).
117. B. A. Ebel, Simulated unsaturated flow processes after wildfire and interactions with slope aspect. *Water Resour. Res.* **49**, 8090–8107 (2013).
118. S. F. Murphy, R. B. McCleskey, D. A. Martin, J. A. M. Holloway, J. H. Writer, Wildfire-driven changes in hydrology mobilize arsenic and metals from legacy mine waste. *Sci. Total Environ.* **743**, 140635 (2020).
119. S. F. Murphy, R. B. McCleskey, D. A. Martin, J. H. Writer, B. A. Ebel, Fire, flood, and drought: Extreme climate events alter flow paths and stream chemistry. *J. Geophys. Res. Biogeo.* **123**, 2513–2526 (2018).
120. U. Silins, K. D. Bladon, E. N. Kelly, E. Esch, J. R. Spence, M. Stone, M. B. Emelko, S. Boon, M. J. Wagner, C. H. S. Williams, I. Tichkowsky, Five-year legacy of wildfire and salvage

logging impacts on nutrient runoff and aquatic plant, invertebrate, and fish productivity. *Ecohydrology* **7**, 1508–1523 (2014).
121. M. B. Emelko, M. Stone, U. Silins, D. Allin, A. L. Collins, C. H. S. Williams, A. M. Martens, K. D. Bladon, Sediment-phosphorus dynamics can shift aquatic ecology and cause downstream legacy effects after wildfire in large river systems. *Glob. Chang. Biol.* **22**, 1168–1184 (2016).
122. A. M. Martens, U. Silins, H. C. Proctor, C. H. S. Williams, M. J. Wagner, M. B. Emelko, M. Stone, Long-term impact of severe wildfire and post-wildfire salvage logging on macroinvertebrate assemblage structure in Alberta's Rocky Mountains. *Int. J. Wildl. Fire* **28**, 738–749 (2019).
123. S. H. Cannon, E. R. Bigio, E. Mine, A process for fire-related debris flow initiation, Cerro Grande Fire, New Mexico. *Hydrol. Process.* **15**, 3011–3023 (2001).
124. J. A. Moody, D. A. Martin, Initial hydrologic and geomorphic response following a wildfire in the Colorado front range. *Earth Surf. Process. Landforms.* **26**, 1049–1070 (2001).
125. T. A. Earles, K. R. Wright, T. E. Langan, Urban drainage system impacts from the Cerro Grande Wildfire. *Glob. Solut. Urban Drain*, 1–14 (2004).
126. D. V. Malmon, S. L. Reneau, D. Katzman, A. Lavine, J. Lyman, Suspended sediment transport in an ephemeral stream following wildfire. *Case Rep. Med.* **112**, 2006 (2007).
127. S. L. Reneau, D. Katzman, G. A. Kuyumjian, A. Lavine, D. V. Malmon, Sediment delivery after a wildfire. *Geology* **35**, 151–154 (2007).
128. J. A. Moody, D. A. Martin, S. L. Haire, D. A. Kinner, Linking runoff response to burn severity after a wildfire. *Hydrol. Process.* **22**, 2063–2074 (2008).
129. M. R. Stevens, C. R. Bossong, M. G. Rupert, A. J. Ranalli, E. W. Cassidy, A. D. Druliner, "Post-wildfire hydrologic hazards in the Wildland Urban Interface of Colorado and the Western United States" (Fact Sheet 2007-3036, USGS, 2008).
130. C. C. Rhoades, D. Entwistle, D. Butler, The influence of wildfire extent and severity on streamwater chemistry, sediment and temperature following the Hayman Fire, Colorado A. *International.* **20**, 430–442 (2011).
131. P. R. Robichaud, S. A. Lewis, J. W. Wagenbrenner, R. E. Brown, F. B. Pierson, Quantifying long-term post-fire sediment delivery and erosion mitigation effectiveness. *Earth Surf. Process. Landforms.* **45**, 771–782 (2020).
132. K. P. Tsai, H. Uzun, H. Chen, T. Karanfil, A. T. Chow, Control wildfire-induced Microcystis aeruginosa blooms by copper sulfate: Trade-offs between reducing algal organic matter and promoting disinfection byproduct formation. *Water Res.* **158**, 227–236 (2019).
133. S. A. Wright, M. D. Marineau, Turbidity current observations in a large reservoir following a major wildfire. *J. Hydraul. Eng.* **145**, 06019011 (2019).
134. H. Chen, H. Uzun, A. T. Chow, T. Karanfil, Low water treatability efficiency of wildfire-induced dissolved organic matter and disinfection by-product precursors. *Water Res.* **184**, 116111 (2020).
135. M. P. Burke, "Investigation of coupled hydrologic and geochemical impacts of wildfire on Southern California Watersheds," thesis, University of California, Los Angeles, CA (2012).
136. V. G. deWolfe, P. M. Santi, J. Ey, J. E. Gartner, Effective mitigation of debris flows at Lemon Dam, La Plata County, Colorado. *Geomorphology* **96**, 366–377 (2008).
137. K. P. Isaacson, C. R. Proctor, Q. E. Wang, E. Y. Edwards, Y. Noh, A. D. Shah, A. J. Whelton, Drinking water contamination from the thermal degradation of plastics: Implications for wildfire and structure fire response. *Environ. Sci. Water Res. Technol.* **7**, 274–284 (2021).
138. J. H. Writer, A. Hohner, J. Oropeza, A. Schmidt, K. M. Cawley, F. L. Rosario-Ortiz, Water treatment implications after the High Park Wildfire, Colorado. *J. Am. Water Works Assoc.* **106**, E189–E199 (2014).
139. B. A. Ebel, J. A. Moody, Parameter estimation for multiple post-wildfire hydrologic models. *Hydrol. Process.* **34**, 4049–4066 (2020).
140. M. J. Paul, S. D. LeDuc, M. G. Lassiter, L. C. Moorhead, P. D. Noyes, S. G. Leibowitz, Wildfire induces changes in receiving waters: A review with considerations for water quality management. *Water Resour. Res.* **58**, 1–28 (2022).
141. I. M. McCullough, K. S. Cheruvelil, J. F. Lapierre, N. R. Lottig, M. A. Moritz, J. Stachelek, P. A. Soranno, Do lakes feel the burn? Ecological consequences of increasing exposure of lakes to fire in the continental United States. *Glob. Chang. Biol.* **25**, 2841–2854 (2019).
142. R. J. Bixby, S. D. Cooper, R. E. Gresswell, L. E. Brown, C. N. Dahm, K. A. Dwire, Fire effects on aquatic ecosystems: An assessment of the current state of the science. *Freshw. Sci.* **34**, 1340–1350 (2015).
143. G. W. Minshall, Responses of stream benthic macroinvertebrates to fire. *For. Ecol. Manage.* **178**, 155–161 (2003).
144. J. W. Wagenbrenner, B. A. Ebel, K. D. Bladon, A. M. Kinoshita, Post-wildfire hydrologic recovery in Mediterranean climates: A systematic review and case study to identify current knowledge and opportunities. *J. Hydrol.* **602**, 126772 (2021).
145. F. N. Robinne, D. W. Hallema, K. D. Bladon, J. M. Buttle, Wildfire impacts on hydrologic ecosystem services in North American high-latitude forests: A scoping review. *J. Hydrol.* **581**, 124360 (2020).
146. A. M. Kinoshita, A. Chin, G. L. Simon, C. Briles, T. S. Hogue, A. P. O'Dowd, A. K. Gerlak, A. U. Albornoz, Wildfire, water, and society: Toward integrative research in the "Anthropocene". *Anthropocene* **16**, 16–27 (2016).

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