Received: 22 June 2022 | Accepted: 14 October 2023

DOI: 10.1111/1752-1688.13174

RESEARCH ARTICLE

AMERICAN WATER RESOURCES ASSOCIATION JAWRA JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Drinking water under fire: Water utilities' vulnerability to wildfires in the Pacific Northwest

Patrick J. L. Robichaud[1] | **Julie C. Padowski**[2]

[1]School of Geography and the Environment, University of Oxford, Oxford, UK

[2]Center for Environmental Research, Education and Outreach, Washington State University, Pullman, Washington, USA

Correspondence
Patrick J. L. Robichaud, School of Geography and the Environment, University of Oxford, Oxford, UK.
Email: patrick.robichaud@wsu.edu

Funding information
NASA Water Resources Program, Grant/Award Number: 80NSSC19K1197

Abstract

Increased wildfire activity in the western United States can lead to detrimental cascading effects to water quality. After fires, burned areas may experience significant runoff-induced erosion and sediment transport into rivers and reservoirs, which could rapidly overwhelm existing drinking water treatment plants. This paper couples an assessment of wildfire risk with an evaluation of water utility preparedness to understand where key fire-related drinking water vulnerabilities exist. Wildfire risk assessments were constructed and expanded from a commonly used methodology co-developed between researchers and water managers (Edel et al., 2002), to understand drinking water impacts on water quality after wildfires. A water utility preparedness index was created for this study using publicly available information to contextualize how well utilities may be able to respond to water quality degradation after fires. Results indicate that 22% of utilities studied (10% of the population served) were underprepared for fire and 11% of watersheds used were at greater risk of wildfire (9% of the population served). However, nearly three-quarters of utilities (76% of the population served) showed a moderate risk of fire and some need for improved fire preparedness. Information developed here could provide a useful framework from which utility managers can better assess their likely wildfire risk and preparation plans.

KEYWORDS
wildfire, source water, water utilities, preparedness

1 | INTRODUCTION

Drinking water systems, especially in the Western United States, are increasingly vulnerable to climate change as shifts in regional precipitation and temperature patterns alter water supply (Bladon et al., 2014; Hohner et al., 2019), water demands (Cui et al., 2018), and wildfire activity (Abatzoglou & Williams, 2016; Chow et al., 2021; Goss et al., 2020; Robinne et al., 2021). In much of the Pacific Northwest (PNW), hydrologic processes are snow-dominant and summer water availability is strongly tied to winter precipitation. In years when the region experiences warmer, drier conditions, the impacts of changing climatic patterns are particularly pronounced in the late summer (i.e. July, August, September) when regional water demands are high and forested watersheds are at their driest (Wan et al., 2017). These hotter, drier conditions

Paper No. JAWR-22-0082-P of the *Journal of the American Water Resources Association* (JAWR).

Discussions are open until six months from publication.

decrease forest fuel moisture which when coupled with decades of historical fire suppression, have in part supported larger fires and are partially to blame for the severe wildfires seasons the PNW has recently experienced (Abatzoglou et al., 2021; Abatzoglou & Williams, 2016; Halofsky et al., 2020; Keane et al., 2019; Littell et al., 2009).

Wildfires now present a growing and serious challenge in the region. Although drinking water utilities are adept at planning for short-term peak water demands and long-term cumulative increases in total demand, most are not equipped to effectively respond to the immediate and long-term effects wildfires have on watershed dynamics (Pyne, 1984). When fires burn through a forested area, they consume understory vegetation and forest floor organic layer, increasing the erodibility of the exposed soils (Moody & Martin, 2001). At the same time, fires deposit ash and fine sediment reducing soil infiltration capacities and increasing overland runoff (Doerr & Cerdá, 2005). Post-fire rain events can mobilize large volumes of recently burned soil and wildfire ash, rapidly increasing sediment loads and turbidity in adjacent waterways—in some instances orders of magnitude above their normal values (Smith et al., 2011)—filling reservoirs and clogging water intakes (Neris et al., 2021; Wondzell & King, 2003). Post-fire soil and debris erosion can overwhelm existing treatment plant capacities by rapidly increasing and sustaining turbidity levels with dissolved organic matter, eco-toxins, ash, and nutrients (Hohner et al., 2019). These water quality changes can lead to serious consequences for PNW drinking water utilities that have historically relied on forested watersheds as high-quality water sources (Hallema et al., 2016; Hohner et al., 2019; Levin et al., 2002). A clear example of such wildfire threats to drinking water systems occurred in the autumn of 2020, when wildfires in western Oregon burned more than 4,330 km^2 across seven watersheds damaging more than 50 public water system intakes and affecting drinking water availability for over 100,000 people (Abatzoglou et al., 2021; Seeds et al., 2020).

At present, many PNW water utilities, serving millions of customers in the region, rely on water from increasingly fire-prone watersheds. However, water utilities, especially those west of the Cascades Mountains in Oregon and Washington, have traditionally not considered wildfires a threat and many have not yet developed detailed plans for mitigating fire-related water quality impacts (Rust et al., 2019; Smith et al., 2011). In part, this is because there is limited observational or historical data on coupled wildfire-ecohydrological processes for this region from which to base plans, which stem in part from the historically long fire return interval and from the challenges of collecting data over large spatial extents in post-fire environments (Nunes et al., 2018; Smith et al., 2011). This lack of information, when coupled with an increasing threat of fire, raises serious issues for where and how water managers address both the immediate and longer-term effects of wildfire disturbances on source water supplies. As fire activity intensifies, utilities will need to be prepared to respond quickly to dramatic shifts in post-fire water quantity and quality to protect the water of communities across the western United States (Emelko et al., 2011).

Many US utilities have already acknowledged wildfire impacts as a major knowledge gap in planning and operations (Furlong et al., 2016). A recent needs assessment investigating water manager needs related to wildfire impacts in the PNW found that 90% of water utility respondents were concerned about wildfire, with 44% indicating wildfire was a moderate to strong concern (Padowski, 2021). Survey respondents indicated that there was real uncertainty about how treatment operations may be impacted by a significant fire event (73%) and that they did not believe or were unsure if they had access to adequate data or information to make confident decisions about post-fire impacts (85%) (Padowski, 2021). Efforts to develop a framework for helping water utilities prepare for wildfires are evolving (Nunes et al., 2018). However, it is clear that more information about wildfire activity and post-fire impacts on water quality and quantity are critically needed by PNW utilities to evaluate their drinking water treatment capabilities and prepare for, or mitigate against, deteriorated source water quality after wildfires.

1.1 | Wildfire assessment tools and efforts

There is a wealth of public information and tools available to communities and managers who are interested in better preparing for and reacting to wildfire threats (e.g. https://wifire.ucsd.edu/). However, many of these resources were developed by, or for, emergency response teams or forest/land managers and therefore focus on fire and smoke impacts, fire location identification, or assessing vegetation or fuel load impacts pre- or post-burn (e.g., http://www.nwfirescience.org/tools). While these tools are useful for understanding fire impact to the terrestrial system, they rarely specifically examine impacts to local hydrology or water quality, and therefore are of limited use to water utilities who need to understand the coupled impacts of fire damage (e.g., infrastructure, vegetation) and changes to source water conditions. While there are limited resources available to help water utilities understand the impact of natural or anthropogenic hydrologic hazards to water management, such as US Environmental Protection Agency Climate Resilience Evaluation & Awareness Tool (CREAT) (USEPA, 2014), and Corps Climate tool (U.S. Army Corps of Engineers, CorpsClimate, 2021) they did not not include hazard impacts derived from wildfires at the time of our review. This means that water managers, including those in the PNW, who are interested in understanding the impacts of fire to water supply management must piece together information from existing tools or resources to try to anticipate complex biogeochemical impacts to water supplies and what it means for water treatment operations. In reality, most water utilities do not have the resources to invest in this type of self-guided research and investigation.

Realizing this knowledge gap, there have been numerous studies over the past decade aimed at understanding how water supply and watershed hydrology changes after fire events (e.g., Zema, 2021). Many of these studies are performed at the watershed scale, seeking to understand complex system dynamics under unique circumstances. Where fires have been more common, local scale studies have provided useful information in the form of historical accounts of fires and examined the biogeochemical changes that take place (Abraham et al., 2017; Bladon et al., 2014;

Niemeyer et al., 2020; Rhoades et al., 2019) as well as the direct impacts to drinking water utilities (Basso et al., 2021; Hallema et al., 2019; Hohner et al., 2016, 2019; Sham et al., 2013). In contrast, regional and topical syntheses have provided more generalized insights on the frequency of fire events that impact water quality and have simplified and summarized common threats managers face when fires do occur (e.g., Bladon et al., 2014; Emelko et al., 2011; Hallema et al., 2018; Nunes et al., 2018; Rhoades et al., 2019; Shakesby & Doerr, 2006; Smith et al., 2011; Wilson et al., 2018).

However, few efforts provide information about wildfire impacts to water supplies that directly account for the fact that water utility operations have varying abilities to respond to or mitigate these hydrologic changes. Vaillant et al. (2016) investigated the vulnerability of US watersheds to fire from the perspective of the burned area impacts on ecosystem function and services, which include water provision and water treatment, but in a very general context. Robinne et al. (2018) was one of the first studies to look explicitly at fire risk to water resources at the global scale, incorporating over 30 socio-environmental metrics reflecting risk to natural and human systems, indirectly addressing drinking water issues. The Forest to Faucets 2.0 team (Claggett & Morgan, 2018) and Robinne et al. (2018) focused specifically on drinking water impacts across the coterminous United States and the province of Alberta, Canada, respectively, identifying where potential municipal watersheds may be vulnerable to fire. However, neither of these works account for existing water utility plans or infrastructure in place that could potentially mitigate or respond to fire impacts.

1.2 | Objectives

This work integrates publicly available water utility information with water resources risks from fire into a framework that accounts not only for fire risk (e.g., post-fire environmental responses) but water utility operations (e.g., treatment capacity, risk planning, etc.). Through this framework, we present a strategy for better understanding where drinking water operations may be more at risk from wildfire threats. As such, the goals of this paper are to: (1) to summarize and evaluate key existing public information sources about wildfire in the PNW that could potentially be useful to water utilities and (2) to estimate and identify future fire risk and utility preparedness in source watersheds used for drinking water supply in the PNW.

2 | METHODOLOGY

2.1 | Study domain

This study spans the states of Washington, Oregon, and Idaho (Figure 1), a combined area of 643,500 km^2. Embedded within this broader PNW landscape are at least 1.2 million people currently relying on forested watersheds for drinking water. These communities are the focus of this assessment. Within this study area, there are a diverse set of factors influencing fire risk for drinking water utilities including distinctly different climate regions, forest types, and topographies, as well as different institutional rules and regulations for drinking water provision and forest management.

The Cascade Mountains in Oregon and Washington provide a distinct climatological north–south dividing line (Figure 1, red line). The topography on the western side of this mountain range is dominated by steep slopes interspersed with valleys and lowlands where most human activity in the region (i.e., cities of Seattle and Portland) occurs. The majority of landscape is forest (83%), dominated by Douglas-fir and western hemlock forests, followed by agricultural land use (7%) and urban/developed land uses (3.6%). The humid climate west of the Cascade Mountains, in combination with a century of managing forests to exclude fires (Keane et al., 2019), gives this area a long wildfire return interval of 80–300 years (LANDFIRE, 2019). In contrast, the area east of the Cascades (~100,000 km^2) is in a rain shadow that significantly reduces the amount of precipitation the area receives. Here, the landscape is comparatively flatter and supports large areas of agriculture (~3300 km^2) and smaller communities before becoming mountainous again in Idaho and central Oregon. Wildfires are more common in the forested and grassland areas of this drier region which experience a shorter fire return period of 20–100 years (LANDFIRE, 2019).

2.2 | Site selection

No papers, to the knowledge of the authors, explicitly include information about water utility preparedness for fire events in their assessments of wildfire impacts to drinking water sources. Factors such as the type of treatment process used, ability to switch to a different water source, and capacity to mobilize resources to deal with fire impacts all could play important roles in reducing the impacts a drinking water system may face if wildfires were to occur in their source watersheds.

Public records from the USEPA SDWIS Federal Reporting System were used to identify medium- to large-sized water utilities (i.e., those serving more than 10,000 people) in WA, ID and OR that listed surface water as a primary source of water ("Water System Facility Reports," USEPA, 2021). In 2019, this search yielded 46 utilities (19 in WA, 25 in OR, and 2 in ID). For each utility, information was collected to characterize

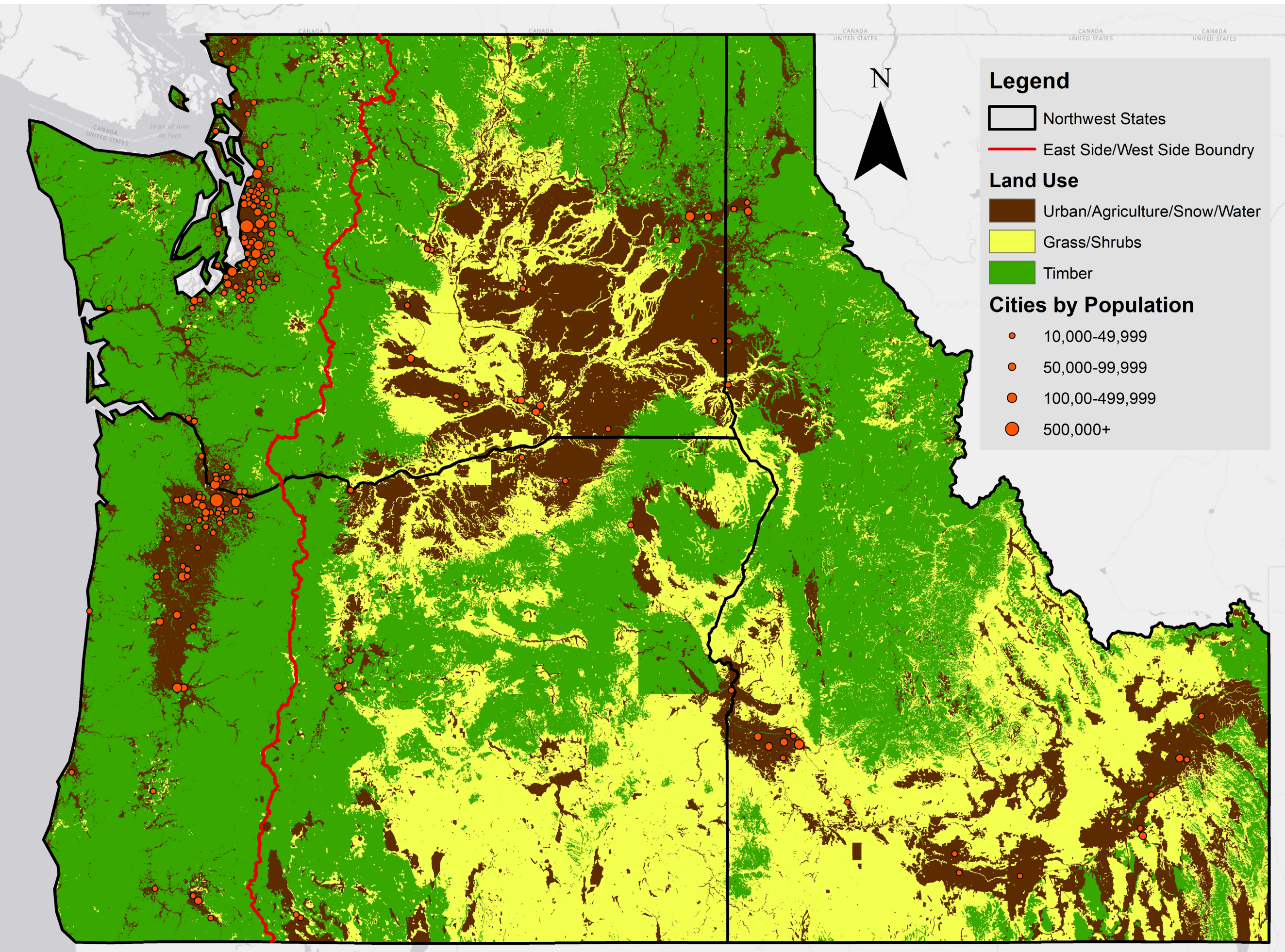

FIGURE 1 Pacific Northwest study domain of Washington, Idaho, and Oregon. This region has two distinct ecoregions to the east and west created by the Cascade Mountains (red line), which creates different dominant climatological and land cover regimes that directly affect fire risk.

general operating and management capacity as well as the degree to which the utility was prepared for fire events. Municipal watershed boundaries were delineated for each utility based on the water sources ($n=46$) used and ranged from relatively small (~20 km^2) to very large (>700,000 km^2).

2.3 | Assessing watershed fire risk

To better understand the relationship between water utility preparedness for fire and watershed fire risk, a watershed fire risk model was developed in two parts. To begin, a simple equation based on basic fire behavior principles was developed using readily available data on weather, topography, and fuels gathered from public data repositories at NOAA and USGS (Table S1). Recognizing the impact that changes in temperature (T) and precipitation (P) may have on water supply availability, many water utilities already take advantage of publicly accessible, location-specific data on temperature and precipitation forecasts (Padowski, 2021). This simple assessment is therefore used to reflect likely expectations that water utilities have about fire risk in their watersheds. We then expand on the simple assessment to incorporate additional biophysical variables that are commonly used in current fire risk assessments in the academic literature to provide a more realistic assessment of watershed risk. While data for this expanded model also come from publicly available data repositories, the methodology and the sources of data may likely be less familiar to those managing water resources. We compare the two assessments to help contextualize water utility preparedness.

2.3.1 | Simple fire risk model

Climate change is increasing summer (June–August) temperatures (T) and changing the timing and volume of summer (June–August) precipitation (P) received across the PNW. Combined, these conditions are expected to intensify and prolong the region's fire season (Abatzoglou &

Williams, 2016). When assessed against readily available information on topography (i.e., slope) and fuel density (using land cover information as a proxy, Keane et al., 2019), a simple estimate of watershed fire risk was developed (Equation 1),

$$R_S = S + \Delta P + \Delta T + \mathrm{LC}, \tag{1}$$

where R_S represents a simplistic assessment of fire risk based on spatial data layers providing information on slope (S) (°), change in mean summer precipitation (ΔP) (mm/month), change in mean summer temperature (ΔT) (°C) for historical (2000–2010) against future (2050–2070) time periods (Table 1, denoted with a *), and land cover classification (LC). Within each layer, it was assumed that cells that had steeper slopes (>14°), positive ΔT values, negative ΔP values, or forested land cover would contribute to greater fire risk to the watershed. In these cases, the cell in the corresponding layer was then assigned a value of 1. Grid cells with slope ≤ 14°, negative ΔT values, land cover representing shrub, grassland, urban, or agricultural areas, or positive ΔP values were each assigned a value of 0. R_S was computed for each grid cell across the entire study domain.

2.3.2 | Expanded fire risk model

The expanded fire risk model builds on the methodology developed by Edel (2002), a commonly referenced report on wildfire readiness and response developed by water utilities and forest managers in Colorado. Using the guiding principles defining fire behavior (e.g., weather, topography, and fuels), Edel (2002) combined climatological, topographical, and biophysical metrics with local watershed characteristics and expert knowledge to generate a weighted composite score that represents fire risk within a given watershed (Equation 2),

$$R_{\mathrm{Edel}} = 0.4(\mathrm{FH}) + 0.35(D) + 0.1(A) + 0.15(S). \tag{2}$$

In Equation (2), the composite watershed fire risk score (R_{Edel}) is comprised of a weighted sum of the fuel hazard (FH) as measured by land use, disturbance regime (D) as measured by past fire regime, aspect (A), and slope (S). The variables in Equation (2) are composed of multiple sub-variables (Table 1, denoted by a #).

This study builds from Equation (2). leveraging additional insights from the recent academic literature (see Table S1) to refine this estimate of fire risk by incorporating seven other commonly used variables that reflect other biophysical characteristics thought to help better assess fire risk in forested watersheds (e.g., Claggett & Morgan, 2018; Robinne et al., 2019) (Table 1). The additional variables result in the expanded fire risk model (Equation 3),

$$R_{\mathrm{WS}} = 0.4(\mathrm{LU} + W + \Delta T + \Delta P + \mathrm{RH}) + 0.35(\mathrm{RD} + \mathrm{PFR}) + 0.1(A) + 0.15(S), \tag{3}$$

where, watershed fire risk (R_{WS}) is a weighted cell-by-cell sum of the slope (S), aspect (A), road density (RD), past fire regimes (PFR), land use (LU), wind velocity (W), relative humidity (RH), change in mean summer (June–August) precipitation (ΔP) [$P_P - P_F$], and change in mean summer (June–August) temperature (ΔT) [$T_F - T_P$], for historical (2000–2010) and future (2050–2070) time periods. Table 1 provides additional detail on the variables used in Equation (3). For information on data sources and resolution, see Table S1.

Geospatial data for each variable in Equations (1 and 3) were obtained from public data sources and clipped to the study region. For each data layer in R_{WS}, gridded values were normalized to a scale of 0–100 using the maximum and minimum values in the study region to produce a common, relative scale across all data layers in the region. Table 1 shows the original classification values assigned across each variable and the normalized value (in parentheses) used in this study. Normalized values (0–100) were assigned such that lower numbers indicated relatively less risk, while higher normalized values represented higher relative risk. R_{WS} was then computed for each grid cell across the entire study domain.

Estimates of fire risk as calculated by R_S and R_{WS} were compared to identify regions where the different methodologies yielded different fire risk results. Fire risk scores for R_S and R_{WS} were normalized on a scale from 0 (lowest risk) to 100 (highest risk) for each grid cell to produce relative, comparable results. To assess the local watershed fire risk, gridded values R_S and R_{WS} layers were each averaged across hydrologic unit code 8 (HUC-8) delineations (Figure 2a,b, respectively).

2.4 | Water utility preparedness

Information on utility ownership (i.e., public, private) and other managing entities within the watershed (e.g., private, state, federal owners) were collected from federal data sources. Water source and distribution information (e.g., number of connections, reservoirs, alternate sources of water) and water treatment operations (e.g., filtration, chemical processes used) were obtained mainly from recent water quality reports published by water utilities. Utility websites were also reviewed for any additional information about plans or protocols designed to respond specifically to fire events. Combined, these data sources were used to estimate each utility's ability to mitigate and respond to wildfires (Table 2). As this paper did not solicit feedback from utilities on assigning different weights or priorities to the indicators used, we make the assumption here that all elements in this preparedness indicator score are weighted equally. This of course could be altered to reflect different

TABLE 1 List of data used in Equations (1 and 3) with reclassification values (in parentheses). All data are mean raster values within a grid cell. Metrics identified with a # represent those used by Edel (2002), and metrics identified with a * represent those used in R_S.

Metric	Category	Value and Classification (Low 0–High 100)				
Slope (°)#*	Slope	0–5	6–20	21–40	>41	
		(25)	(50)	(75)	(100)	
Assumption: Steeper slopes burn faster and fire spreads more easily (Edel, 2002)						
Aspect (degrees)#	Aspect	0–160 or 200–360	160–165 or 195–200	165–175 or 185–195	175–185	
		(25)	(50)	(75)	(100)	
Assumption: Southern facing slopes will receive more sun and thus be drier than other slopes (Edel, 2002)						
Road density (m)#	Disturbance (buffer)	0–100	>100			
		(100)	(0)			
Assumption: Human activity is the primary cause of ignitions, and fires are much more likely to begin closer to a road (Edel, 2002)						
Past fire regimes#	Disturbance (recurrence/severity)	>200 year/low	35–200 year/low-med	<35 year/low-med	35–200 year/high	<35 year/high
		(33)	(33)	(66)	(66)	(100)
Assumption: A prior forest fire will burn the majority of the fuel resulting in less severe forest fires in the next 10–20 years in the future (Edel, 2002; Schmidt, 2002)						
Land use#*	Fuel hazard	Grass	Shrubs	Timber	Developed/Barren	
		(33)	(66)	(100)	(0)	
Assumption: Forests have a higher likelihood of burning and at hotter temperatures than shrubs or grass (Bradshaw, 1984; Hal, 1982)						
Wind (m/s)	Fuel hazard	0–12				
		(0–100)				
Assumption: Windy locations will cause a fire to spread more than non-windy locations (Cruz & Alexander, 2019)						
Temperature summer 2050–2070 (°C)*	Fuel hazard	0–5				
		(0–100)				
Assumption: Increased mean summer (June–August) temperatures will make vegetation more flammable (Bradshaw et al., 1984)						
Temperature summer 2000–2010 (°C)*	Fuel hazard	5–32				
		(0–100)				
Assumption: Higher summer (June–August) temperatures will make vegetation more flammable (Bradshaw et al., 1984)						
Precipitation summer 2050–2070 (mm/month)*	Fuel hazard	0–500				
		(0–100)				
Assumption: Decreased mean summer (June–August) precipitation will result in more intense forest fires (Bradshaw et al., 1984)						
Precipitation summer 2000–2010 (mm/month)*	Fuel hazard	0–7000				
		(0–100)				
Assumption: Decreased summer (June–August) precipitation will result in more intense wildfires (Bradshaw et al., 1984)						
Relative humidity (%)	Fuel hazard	0–35	35–45	45–55	55–65	>65
		(100)	(80)	(60)	(40)	(20)
Assumption: Lower relative humidity will dry fuels making them more likely to burn (Brown et al., 2004)						

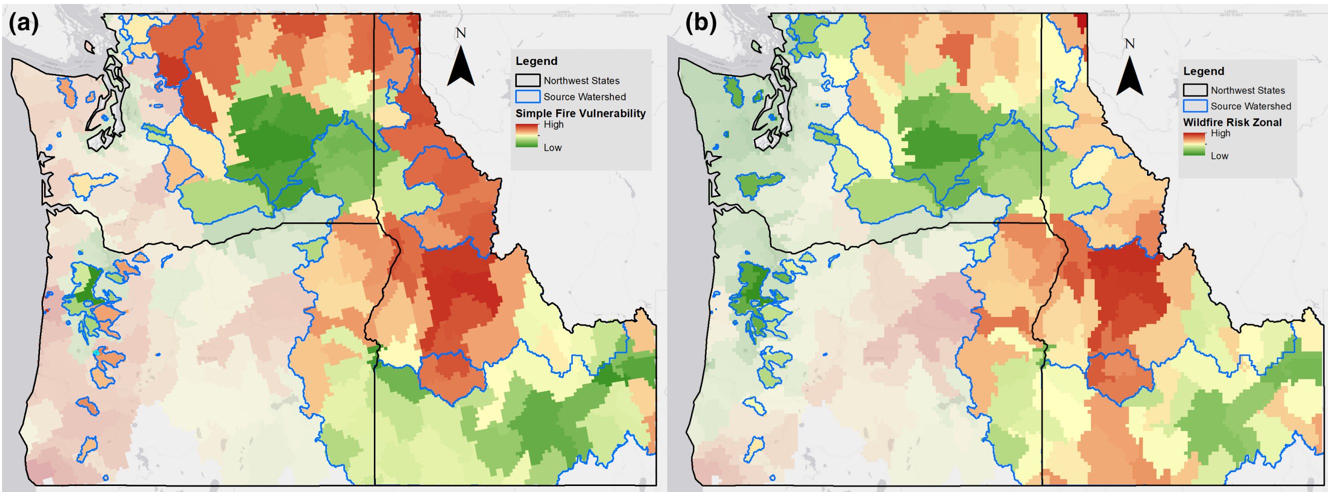

FIGURE 2 Comparison of mean watershed fire risk by hydrologic unit code 8 (HUC-8) boundary using R_S (a) and R_{WS} (b). Areas outside of study site source watersheds are faded. Blue lines indicate source watershed boundaries.

priorities by individual utilities. Finally, the authors also fully recognize that the publicly available data used in this study may not fully represent a particular utility's full portfolio of response options in the face of a fire event; rather, this study provides a baseline of known information from which additional data could be incorporated.

To estimate the relative degree to which water utilities were prepared for fire, data identified in Table 2 were classified and normalized where needed. All metrics were left equally weighted and summed to obtain an overall preparedness score. Summed scores were normalized from 0 to 1, where 1 represented maximum relative risk.

3 | RESULTS AND DISCUSSION

3.1 | Watershed fire risk

Two estimates of watershed fire risk were developed in this study to compare where likely significant deviations in perceptions of fire risk may occur. Figure 2 displays the degree of fire risk averaged across HUC-8 watershed boundaries in the PNW as developed using threshold limits on basic, easily accessible, fire behavior-related data (R_S) (Figure 2a), which represented a fire future based on basic assumptions about fire risk using Equation (1). In comparison, R_{WS} (based on Equation 3) represents a more nuanced fire risk assessment, updating Equation (1) with insights from recent academic literature, while also using publicly available data (Figure 2b). These two maps represent two potential methods for estimating fire risk from publicly available data (i.e., data a water utility could easily access and use) and provide two different scenarios of future fire risk.

Table 3 shows the percent change in fire risk for all basins in the study area. Across all HUC 8 watersheds, there was median decrease of 5% in fire risk scores when comparing R_S to R_{WS} estimates, with significant differences between scores occurring throughout most of the PNW, including our study watersheds. This analysis showed that 39.7% of the HUC8 watersheds had a –10% to –50% change between the two methods. In part, this difference arises due to the granularity of the data used in each equation. For instance, to simplify the calculation, variable data in Rs are converted to binary data, whereas R_{WS} assesses variables along a categorical scale and range. However, the majority of the variation stems from the more nuanced data integrated into R_{WS}, which reflects not just vegetation cover, but land use and aspect, and not just temperature and precipitation, but relative humidity and wind velocity as well (Abatzoglou & Williams, 2016). Combined, this creates significant disagreement on the degree of fire risk across most of the study region. While a more rigorous validation of these R values against other modeled data was beyond the scope of work here, the comparison of these two methods is still useful for providing context about the extent to which water utilities prepare for impacts from fire. For the purposes of this paper, we use only R_{WS} for in the assessments presented in the remainder of this paper.

3.2 | Water utility preparedness

Fire risk assessments are useful for understanding biophysical and environmental-related risks, but cannot provide insights into a water utility's capacity to respond to fire events or what likely post-fire impacts to water sources may be, both of which are important to water utility

AMERICAN WATER RESOURCES ASSOCIATION JAWRA JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

TABLE 2 Listing of data used in creation of water utility preparedness along with classification. Higher values represent greater relative risk.

Variable	Categories	Normalized by
Land ownership	Number of owners (from 1 to 7)	$\frac{n}{\text{max. value}}$
Assumption: Single ownership of a watershed makes management decisions easier while multiple ownership makes management more difficult (Canning & Ryan, 2020)		
Source diversity	Access to surface water only	1
	Access to surface + groundwater	0
Assumption: Groundwater source is more likely to be undisturbed compared to a surface watershed (Becker et al., 2018)		
Source redundancy	Number of sources (from 1 to 3)	$1 - \frac{n}{\text{max. value}}$
Assumption: Additional reservoirs or intakes could augment the primary source and possibly allow the water utility to stop intaking at the contaminated source (Becker et al., 2018)		
Treatment technology	No treatment	1.0
	Direct filtration	0.8
	Two-stage filtration	0.6
	Conventional filtration	0.4
	Filtration plus	0.2
	Advanced filtration	0
Assumption: Increased treatment will remove more contaminants (Becker et al., 2018)		
Diversion point	Withdraw from a point in stream	1
	Withdraw from a point in a reservoir	0
Assumption: Dam at diversion point will allow sediment to settle out of water prior to reaching the intake (Canning & Ryan, 2020)		
Fire planning	No plan found	1
	Plan mentioned, not detailed	0.67
	Plan identified, not fire-specific	0.33
	Plan identified, fire-specific	0
Assumption: Water utilities with a fire plan are better prepared and have devoted more resources towards this issue (Canning & Ryan, 2020)		
Service capacity	Percent of the population being served	$\frac{\text{(connections / population)}}{\text{maxvalue}}$
Assumption: The greater the portion of a population served by a single utility, the greater the potential for large-scale disruption (Sham et al., 2013)		
Income ($)	Median income by city ($36–92k)	$1 - \frac{n}{\text{max. value}}$
Assumption: Higher income increases likelihood the utility has more funds for mitigation or preparedness (North East Water: Governance Framework, 2019)		
Slope (%)	Percentage of watershed greater than 34° slope	
Assumption: Steeper slopes are more difficult to access and manage in either pre- or post-fire scenarios (Lentile et al., 2006)		
Forest cover (%)	Percentage of watershed that is forested	
Assumption: Larger forested areas are more difficult to access and manage in either pre- or post-fire scenarios (Wondzell & King, 2003)		

managers. Across all samples, the mean normalized preparedness score for utilities was 44.2, with the lowest (most prepared) score equaling 28.2 and the highest (least prepared) score of 59.9. Across the three states evaluated, the mean score for utilities was 43.8 ± 8.6 in Oregon (n = 25), 45.8 ± 8.6 in Washington (n = 19) and 33.4 ± 1.7 in Idaho (n = 2).

Water utility planning and operation documents were collected where publicly available to better understand how prepared water utilities in the region are for wildfire events (Table 2). Of the 46 utilities sampled, 9% had no publicly-shared plans that specifically mentioned wildfire or how they might respond to wildfire impacts should a fire in their watershed occur. Many more utilities (57%) mention or provide links to planning documents that outlined decisions about dealing with natural hazards, although these plans were rarely focused on wildfire impacts in particular. The remainder of utilities (35%) had plans that specifically called out fire as a potential hazard and outlined plans for responding to or preparing for fire impacts. *Source water redundancy* was characterized by the number of different sources of water a utility can access. Here, it was assumed that redundancy through multiple source water options is advantageous as it allows a utility to switch water supplies with minimal interruption if a primary source becomes contaminated from wildfire impacts. Just under half of utilities had a single source (48%) for water supply while the

TABLE 3 Summary of the percent of basins in the study area by fire risk score percent change category when comparing between R_S and R_{WS} estimates.

R_S–R_{WS} change	HUC count	Percent (%)
−50% to −10%	79	39.7
−10% to 0%	51	25.6
0% to 10%	32	16.1
10% to 50%	36	18.1
50% to 100%	1	0.5

remainder had either two (50%) or 3+ (2%) sources of water supply. *Source water diversity* was also explored. Having a combination of surface water and groundwater supplies is advantageous because groundwater is often protected from fire and potential contaminants events on the surface, such as a post-fire erosion event. Here, 67% of utilities had access to only surface water supplies while 33% had surface and groundwater supplies. *Water reservoirs* can act as settling basins, allowing particulate matter to settle out of the water column, resulting in less turbid water should heavy contamination occur post-fire. Nearly three-quarters of utilities (74%) had their water intake inside a reservoir. *Water treatment technology* is designed to remove suspended solids from the source water and can potentially clean contaminated water if a post-fire erosion event occurs (Emelko et al., 2011). Across all sampled utilities, the most common method of drinking water treatment was two stage filtration (67%), followed by conventional filtration (26%) and direct filtration (7%) which includes sand filters, or no filters and only chlorine. *Watershed ownership* can consist of one or more managing entities and can lead to fragmented management strategies that may complicate how fire prevention and suppression is implemented. About half of utilities had one landowner (52%), while 48% had two or more landowners. *Watershed terrain*, classified as the percent of forested area within a watershed that has a slope greater than 34°, can also play a significant role in how much of the watershed a utility can actually manage. Forested areas or steep terrain can be difficult to access for pre-fire management or post-fire recovery and are highly susceptible to post-fire erosion. Other water utility characteristics, such service extent (connection/population) and the median income in each city serviced, were also included. Source information for water utility preparedness data is included in Table S2.

3.3 | Wildfire and preparedness risk assessment

The impact of wildfire on water utility operations is a product of both watershed fire risk and the degree to which a utility is prepared to deal with fire-related impacts (for a list of utilities assessed here, see Table S3). This work leverages the novel dataset of publicly available water utility preparedness information created to examine where fire risk and utility preparedness may be well- or mis-aligned (Figure 3). In general, more utilities with higher fire risk scores (Groups 7, 8, 9) were found in Oregon ($n=3$) than in WA ($n=1$) or ID ($n=1$) and represent a small proportion of the utilities examined (11%). The number of utilities with a higher preparedness risk score were relatively similar for WA ($n=4$) and OR ($n=6$), representing 22% of the sample. Neither of the two utilities in ID fell into this high-risk category.

Results were also contextualized to understand how risk and preparedness may impact the broader population relying on surface water sources for drinking water. When sites were assessed along both axes of Figure 3, nearly three-quarters all the watersheds evaluated (72%) ranked as either medium or high fire risk and were used by utilities who were less/moderately prepared for fire (Groups 9, 8, 6, and 5). This group represents 76% of the sampled service population. Yet, of these, only one utility (representing 0.01% of the sampled service population) was categorized as being both less prepared for and at high risk for fire (Group 9). In general, Groups 3, 6, and 9 (representing 10% of the sampled service population) had the highest scores for preparedness, indicating they were relatively less prepared, and showed risks associated with watershed terrain, source redundancy, source diversity, diversion points, and service capacity. In contrast, Groups 1, 4, and 7, or 17% of the sampled service population, were identified as relatively well-prepared with all three groups presenting especially low scores for watershed terrain, land ownership, treatment technology, source redundancy, source diversity, and diversion points. Groups 7, 8, and 9 (9% of the sampled service population) represent those sites with the highest wildfire risk and have relatively high scores because of the number of land owners in the watershed, service capacity, and their less advanced treatment technology. In contrast, Groups 1, 2 and 3 (9% of the sampled service population) display a relatively low wildfire risk and had fewer landowners and more source redundancy.

3.4 | Management implications

This work was designed to provide additional insight and context into the growing threat that wildfires pose to drinking water utility operations. While only a small number of utilities (and a correspondingly small portion of the service population) were found to be at greatest risk (i.e., Group 9), the fact that nearly three-quarters of all sites evaluated (representing 76% of the population) were both at relatively higher risk for,

AMERICAN WATER RESOURCES ASSOCIATION JAWRA JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

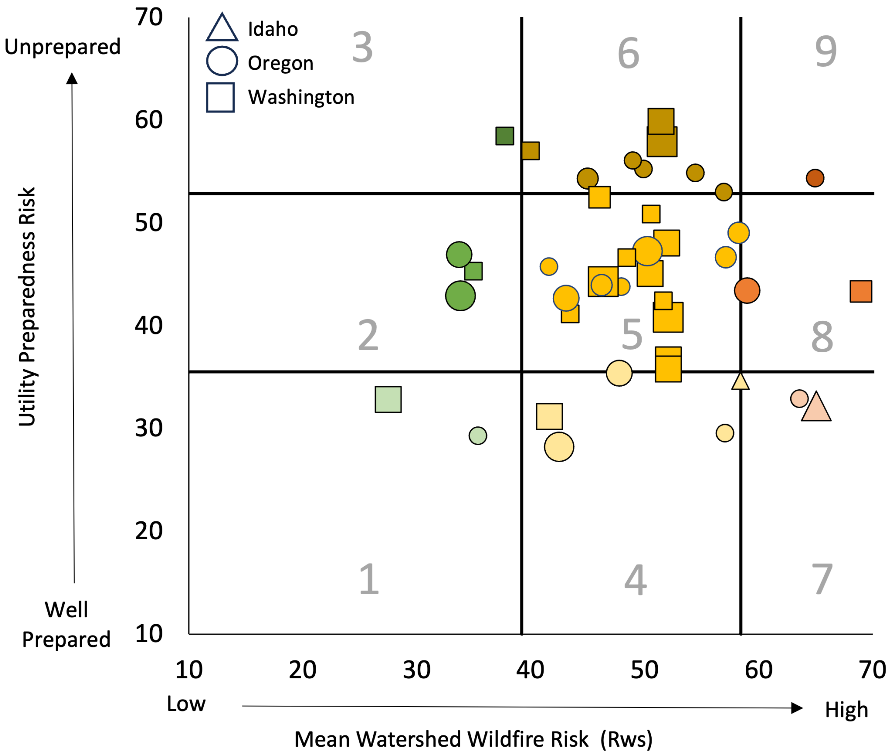

FIGURE 3 Combined water utility preparedness and watershed risk for fire (triangles = ID, squares = WA, circles = OR). Data are divided into nine groups for discussion purposes based on ±1 SD of the mean value for R_{WS} and utility preparedness across all samples. Group 1 sites are least at risk of fire and fire impacts, whereas Group 9 are at greatest risk of fire and fire impacts. Larger marker size correlates to larger population served by utility.

and under prepared for, fire (Groups 9, 8, 6, and 5) highlights the importance of the need for data that is useful to resource managers and helps contextualize the important knowledge gaps that still exist. While this work is but an initial step towards meaningfully linking wildfire information and water utility management, it is particularly important as water utilities become aware of the risks of wildfire and explore proactive strategies to combat negative water quality consequences from fire. Strategies currently being discussed include pre-fire mitigation aimed at reducing fire risk to prescribed burns that are lower intensity and reduce the likelihood of degraded water quality events. Some utilities are considering post-fire mitigation actions, such as mulching, to prevent erosion after fires occur. Others are looking forward and considering treatment plant upgrades that would allow them to improve their treatment process. These and other nuances are not explicitly captured in this work, and the preparedness index assumes that all metrics included have equal weight to a utility when considering how to prepare for fire. In reality, each metric may need to be weighted more or less depending on the specific utility, and additional metrics may need to be added to more accurately represent a specific site. Future work building from this methodology would do well to work directly with utilities to identify how preparedness weights may need to be adjusted to more accurately reflect an organization's reality, and emphasizes that without the right information, the impact of any action pursued by utilities may or may not be fully realized. Through the integrated framework discussed here, we lay a path forward for work that more explicitly integrates water utility perceptions and values about wildfire risk (e.g., using a structured decision-making approach, Marttunen et al., 2017) into how both wildfire risk and utility preparedness are assessed.

As with any initial efforts, we acknowledge that future work is needed both to refine the metrics used in this framework and address some of the current limitations of the work presented here. For instance, the metrics used in this assessment could be expanded to better capture other aspects of wildfire risk or water utility preparedness. With respect to wildfire risk, other factors such as soil texture properties and rainfall can be important for evaluating post-wildfire risk. Areas with silt or clay loam are more erodible compared to sandy or gravelly loam soils. Rainfall intensity or the likelihood of rain-on-snow events also could greatly affect post-fire erosion processes and alter the risks posed to water utilities. With respect to water utility preparedness, we only reviewed three Northwest states (Washington, Oregon, and Idaho), and only used relatively static data available on the public domain without consultation from water utilities themselves. Next steps could include expanding the geographical extent and working with utilities to better determine what steps water utilities are taking, or could be taking, to mitigate wildfire risk.

4 | CONCLUSION

Wildfires are predicted to increase in size and intensity due to climate change. Fire events in forested areas that have historically served as source watersheds for drinking water utilities have the potential to significantly and negatively impact source water quality, threatening the water supply for millions of people across the PNW. This paper presented a novel framework for exploring fire risk in drinking water source watersheds based on an integrated biophysical and institutional assessment of water supply and water utility management. Assuming not all utilities have sophisticated methods for predicting their future level of fire risk, we modeled two sets of outcomes. One (R_S) used basic, easy to obtain, fire behavior data and a simplified "threshold" approach for estimating fire risk that could be potentially used by any water utility. The other (R_{WS}) offered a revised approach that built on recent academic literature and available data to produce a more nuanced understanding of risk. The resulting spatial differences in potential fire risk produced by the two methods emphasize the need for a consistent set of information about future fire, especially for water managers. At the same time, estimates of water utility preparedness were derived from publicly available data, and while relatively coarse, provide a base-level understanding of utility decision-making in the face of fire. This set of data is especially valuable, as over-planning could result in a water utility spending more resources on preparing for unlikely event whereas under-planning could leave a utility severely disadvantaged should a fire occur. This is particularly true as results from this work generally indicated that watersheds in central Idaho, northern Washington, and central Oregon had higher wildfire risk. Most utilities studied showed signs of being at greater risk to wildfire but were less prepared to deal with fire impacts should they occur. In particular, water utilities on the western side of the Cascades had a higher percentage of underprepared utilities compared to utilities on the eastern side where fire risk is more common.

Finally, this study is but a starting point to understand how fire risk potentially impacts drinking water operations and what water utilities could do to prepare for such events. Our work offers an integrated framework that could be used by both managers and researchers for evaluating these risks, but further efforts aimed at refining the metrics used to better fit other locations and utilities are needed. Collaboration between managers and scientists will be key to making these improvements if they are to provide timely and relevant information for managing our drinking water resources in the face of a changing wildfire future.

AUTHOR CONTRIBUTIONS

Patrick J. L. Robichaud: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing – original draft. **Julie C. Padowski:** Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; writing – review and editing.

ACKNOWLEDGMENTS

The authors thank Peter R. Robichaud and Amanda Hohner for their early reviews and thoughtful comments on the manuscript. This work was funded by NASA Water Resources Program—Grant Number 80NSSC19K1197.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The data used to support this study are openly available in the USEPA SDWIS Federal Reports at https://ordspub.epa.gov/ords/sfdw_pub/r/sfdw/sdwis_fed_reports_public/200 and available in HydroShare at https://doi.org/10.4211/hs.c874f49441144c1791d717c528092c8e (Robichaud & Padowski, 2023; "Water System Facility Reports," USEPA, 2021).

ORCID

Patrick J. L. Robichaud https://orcid.org/0000-0002-7608-922X

REFERENCES

Abatzoglou, J.T., D.E. Rupp, L.W. O'Neill, and M. Sadegh. 2021. "Compound Extremes Drive the Western Oregon Wildfires of September 2020." *Geophysical Research Letters* 48: e2021GL092520.

Abatzoglou, J.T., and A.P. Williams. 2016. "Impact of Anthropogenic Climate Change on Wildfire across Western US Forests." *Proceedings of the National Academy of Sciences of the United States of America* 113: 11770–75.

Abraham, J., K. Dowling, and S. Florentine. 2017. "Risk of Post-Fire Metal Mobilization into Surface Water Resources: A Review." *Science of the Total Environment* 599–600: 1740–55.

Basso, M., M. Mateus, T.B. Ramos, and D.C.S. Vieira. 2021. "Potential Post-Fire Impacts on a Water Supply Reservoir: An Integrated Watershed-Reservoir Approach." *Frontiers in Environmental Science* 9: 684703.

Becker, W.C., A. Hohner, F. Rosario-Ortiz, and J. DeWolfe. 2018. "Preparing for Wildfires and Extreme Weather: Plant Design and Operation Recommendations." *Journal: American Water Works Association* 110: 32–40.

Bladon, K.D., M.B. Emelko, U. Silins, and M. Stone. 2014. "Wildfire and the Future of Water Supply." *Environmental Science & Technology* 48: 8936–43.

Bradshaw, L.S. 1984. *The 1978 National Fire-Danger Rating System: Technical Documentation*. Ogden, Utah, USA: US Department of Agriculture, Forest Service, Intermountain Forest and Range.

Bradshaw, L.S., J.E. Deeming, R.E. Burgan, and J.D. Cohen. 1984. *The 1978 National Fire-Danger Rating System: Technical Documentation*. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Brown, T.J., B.L. Hall, and A.L. Westerling. 2004. "The Impact of Twenty-First Century Climate Change on Wildland Fire Danger in the Western United States: An Applications Perspective." *Climatic Change* 62: 365–88.

Canning, A., and G. Ryan. 2020. *National Good Practice Operational Guidelines for Bushfire Management for the Australian Water Industry*. Melbourne, Australia: Water Services Association of Australia.

Chow, A., T. Karanfil, and R. Dahlgren. 2021. "Wildfires are Threatening Municipal Water Supplies." *Eos* 102. https://doi.org/10.1029/2021EO161894.

Claggett, S., and R. Morgan. 2018. "USFS Looks to the Future in Upcoming Forests to Faucets Analysis." *Journal-American Water Works Association* 110: 41–47.

Cruz, M.G., and M.E. Alexander. 2019. "The 10% Wind Speed Rule of Thumb for Estimating a Wildfire's Forward Rate of Spread in Forests and Shrublands." *Annals of Forest Science* 76: 44.

Cui, R.Y., K. Calvin, L. Clarke, M. Hejazi, S. Kim, P. Kyle, P. Patel, S. Turner, and M. Wise. 2018. "Regional Responses to Future, Demand-Driven Water Scarcity." *Environmental Research Letters* 13: 094006.

Doerr, S.H., and A. Cerdá. 2005. "Fire Effects on Soil System Functioning: New Insights and Future Challenges." *International Journal of Wildland Fire* 14: 339.

Edel, S. 2002. "Colorado Wildland Urban Interface Hazard Assessment Methodology." Colorado State Forest Service. https://static.colostate.edu/client-files/csfs/documents/ColoradoWUIHazardAssessmentFinal.pdf.

Emelko, M.B., U. Silins, K.D. Bladon, and M. Stone. 2011. "Implications of Land Disturbance on Drinking Water Treatability in a Changing Climate: Demonstrating the Need for "Source Water Supply and Protection" Strategies." *Water Research* 45: 461–72.

Furlong, C., S. De Silva, L. Guthrie, and R. Considine. 2016. "Developing a Water Infrastructure Planning Framework for the Complex Modern Planning Environment." *Utilities Policy* 38: 1–10.

Goss, M., D.L. Swain, J.T. Abatzoglou, A. Sarhadi, C.A. Kolden, A.P. Williams, and N.S. Diffenbaugh. 2020. "Climate Change is Increasing the Likelihood of Extreme Autumn Wildfire Conditions across California." *Environmental Research Letters* 15: 094016.

Hal, A. 1982. "Aids to Determining Fuel Models for Estimating Fire Behavior." USDA Forest Service General Technical Report. https://agroambient.gva.es/documents/162905929/169203680/Anderson+1982/41f60b20-c5e1-4082-827b-49eea207d19f.

Hallema, D.W., A.M. Kinoshita, D.A. Martin, F.-N. Robinne, M. Galleguillos, S.G. McNulty, G. Sun, K.K. Singh, R.S. Mordecai, and P.F. Moore. 2019. *Unasylva 251: Forests: Nature-Based Solutions for Water: Fire, Forests and City Water Supplies*. Rome, Italy: Food and Agriculture Organizaiton of the United Nations.

Hallema, D.W., R. Moussa, G. Sun, and S.G. McNulty. 2016. "Surface Storm Flow Prediction on Hillslopes Based on Topography and Hydrologic Connectivity." *Ecological Processes* 5: 13.

Hallema, D.W., G. Sun, P.V. Caldwell, S.P. Norman, E.C. Cohen, Y. Liu, K.D. Bladon, and S.G. McNulty. 2018. "Burned Forests Impact Water Supplies." *Nature Communications* 9: 1307.

Halofsky, J.E., D.L. Peterson, and B.J. Harvey. 2020. "Changing Wildfire, Changing Forests: The Effects of Climate Change on Fire Regimes and Vegetation in the Pacific Northwest, USA." *Fire Ecology* 16: 4.

Hohner, A.K., K. Cawley, J. Oropeza, R.S. Summers, and F.L. Rosario-Ortiz. 2016. "Drinking Water Treatment Response Following a Colorado Wildfire." *Water Research* 105: 187–98.

Hohner, A.K., C.C. Rhoades, P. Wilkerson, and F.L. Rosario-Ortiz. 2019. "Wildfires Alter Forest Watersheds and Threaten Drinking Water Quality." *Accounts of Chemical Research* 52: 1234–44.

Keane, R.E., K. Gray, B. Davis, L.M. Holsinger, and R. Loehman. 2019. "Evaluating Ecological Resilience across Wildfire Suppression Levels under Climate and Fuel Treatment Scenarios Using Landscape Simulation Modelling." *International Journal of Wildland Fire* 28: 533.

LANDFIRE. 2019. "US Geologic Survey." https://www.landfire.gov/viewer/viewer.html?extent=-121.227578057513,44.9163507220303,-116.364368429388,49.0021240421711.

Lentile, L.B., F.W. Smith, and W.D. Shepperd. 2006. "Influence of Topography and Forest Structure on Patterns of Mixed Severity Fire in Ponderosa Pine Forests of the South Dakota Black Hills, USA." *International Journal of Wildland Fire* 15: 557–66.

Levin, Ronnie B., Paul R. Epstein, Tim E. Ford, Winston Harrington, Erik Olson, and Eric G. Reichard. 2002. "U.S. Drinking Water Challenges in the Twenty-First Century." *Environmental Health Perspectives* 110: 43–52.

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling. 2009. "Climate and Wildfire Area Burned in Western US Ecoprovinces, 1916–2003." *Ecological Applications* 19: 1003–21.

Marttunen, M., J. Lienert, and V. Belton. 2017. "Structuring Problems for Multi-Criteria Decision Analysis in Practice: A Literature Review of Method Combinations." *European Journal of Operational Research* 263: 1–17.

Moody, J.A., and D.A. Martin. 2001. "Initial Hydrologic and Geomorphic Response Following a Wildfire in the Colorado Front Range." *Earth Surface Processes and Landforms* 26: 1049–70.

Neris, J., C. Santin, R. Lew, P.R. Robichaud, W.J. Elliot, S.A. Lewis, G. Sheridan, et al. 2021. "Designing Tools to Predict and Mitigate Impacts on Water Quality Following the Australian 2019/2020 Wildfires: Insights from Sydney's Largest Water Supply Catchment." *Integrated Environmental Assessment and Management* 17: 1151–61.

Niemeyer, R.J., K.D. Bladon, and R.D. Woodsmith. 2020. "Long-Term Hydrologic Recovery after Wildfire and Post-Fire Forest Management in the Interior Pacific Northwest." *Hydrological Processes* 34: 1182–97.

North East Water: Governance Framework. 2019. "North East Water." https://www.wsaa.asn.au/sites/default/files/publication/download/Appenxix%20A%20-%20North%20East%20CIR.pdf.

Nunes, J.P., S.H. Doerr, G. Sheridan, J. Neris, C. Santín, M.B. Emelko, U. Silins, P.R. Robichaud, W.J. Elliot, and J. Keizer. 2018. "Assessing Water Contamination Risk from Vegetation Fires: Challenges, Opportunities and a Framework for Progress." *Hydrological Processes* 32: 687–94.

Padowski, J. 2021. "Assessing the Need for Fire-Related Decision-Support Tools for Water Management in the Pacific Northwest, USA." Washington State Univeristy. https://s3.wp.wsu.edu/uploads/sites/95/2021/09/SurveySummary_Final.pdf.

Pyne, S.J. 1984. *Introduction to Wildland Fire. Fire Management in the United States*. New York, USA: John Wiley & Sons.
Rhoades, C.C., J.P. Nunes, U. Silins, and S.H. Doerr. 2019. "The Influence of Wildfire on Water Quality and Watershed Processes: New Insights and Remaining Challenges." *International Journal of Wildland Fire* 28: 721–25.
Robichaud, P., and J. Padowski. 2023. "Drinking Water Under Fire: Water Utilities' Vulnerability to Wildfires in the Pacific Northwest." https://doi.org/10.4211/hs.75d565f76a9c4f04990b1538201010d1.
Robinne, F., D.W. Hallema, K.D. Bladon, M.D. Flannigan, G. Boisramé, C.M. Bréthaut, S.H. Doerr, et al. 2021. "Scientists' Warning on Extreme Wildfire Risks to Water Supply." *Hydrological Processes* 35: e14086. https://doi.org/10.1002/hyp.14086.
Robinne, F.-N., K.D. Bladon, C. Miller, M.-A. Parisien, J. Mathieu, and M.D. Flannigan. 2018. "A Spatial Evaluation of Global Wildfire-Water Risks to Human and Natural Systems." *Science of the Total Environment* 610–611: 1193–206.
Robinne, F.N., K.D. Bladon, U. Silins, M.B. Emelko, M.D. Flannigan, M.-A. Parisien, X. Wang, S.W. Kienzle, and D.P. Dupont. 2019. "A Regional-Scale Index for Assessing the Exposure of Drinking-Water Sources to Wildfires." *Forests* 10: 384.
Rust, A.J., S. Saxe, J. McCray, C.C. Rhoades, and T.S. Hogue. 2019. "Evaluating the Factors Responsible for Post-Fire Water Quality Response in Forests of the Western USA." *International Journal of Wildland Fire* 28: 769.
Schmidt, K.M. 2002. "Development of Coarse-Scale Spatial Data for Wildland Fire and Fuel Management." U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://books.google.co.uk/books?id=4odGAAAAYAAJ.
Seeds, J., S. Tourney, R. Gross, K. Rowden, K. Madsen, M. Young, D. Thomas, and D. Callery. 2020. "Erosion Threat Assessment and Reduction Team: Water Quality/Drinking Water Supply Resource Report." State of Oregon. https://www.oregon.gov/deq/wildfires/Documents/ETARTwqReportF.pdf.
Shakesby, R.A., and S.H. Doerr. 2006. "Wildfire as a Hydrological and Geomorphological Agent." *Earth-Science Reviews* 74: 269–307.
Sham, C.H., M.E. Tuccillo, and J. Rooke. 2013. *Effects of Wildfire on Drinking Water Utilities and Best Practices for Wildfire Risk Reduction and Mitigation*. Waltham, Massachusetts, USA: Water Research Foundation.
Smith, H.G., G.J. Sheridan, P.N.J. Lane, P. Nyman, and S. Haydon. 2011. "Wildfire Effects on Water Quality in Forest Catchments: A Review with Implications for Water Supply." *Journal of Hydrology* 396: 170–92.
U.S. Army Corps of Engineers, CorpsClimate. 2021. "Climate Preparedness and Resilience." https://www.usace.army.mil/corpsclimate/.
USEPA. 2014. "Climate Resilience Evaluation and Awareness Tool (CREAT) Risk Assessment Application for Water Utilities." https://www.epa.gov/crwu/climate-resilience-evaluation-and-awareness-tool-creat-risk-assessment-application-water.
USEPA. 2021. "Water System Facility Reports." https://ordspub.epa.gov/ords/sfdw/f?p=108:12::::RP.
Vaillant, N.M., C.A. Kolden, and A.M.S. Smith. 2016. "Assessing Landscape Vulnerability to Wildfire in the USA." *Current Forestry Reports* 2: 201–13.
Wan, W., J. Zhao, H.-Y. Li, A. Mishra, L. Ruby Leung, M. Hejazi, W. Wang, et al. 2017. "Hydrological Drought in the Anthropocene: Impacts of Local Water Extraction and Reservoir Regulation in the U.S.: Hydrological Drought in the Anthropocene." *Journal of Geophysical Research: Atmospheres* 122: 11313–28.
Wilson, C., S.K. Kampf, J.W. Wagenbrenner, and L.H. MacDonald. 2018. "Rainfall Thresholds for Post-Fire Runoff and Sediment Delivery from Plot to Watershed Scales." *Forest Ecology and Management* 430: 346–56.
Wondzell, S.M., and J.G. King. 2003. "Postfire Erosional Processes in the Pacific Northwest and Rocky Mountain Regions." *The Effect of Wildland Fire on Aquatic Ecosystems in the Western USA* 178: 75–87.
Zema, D.A. 2021. "Postfire Management Impacts on Soil Hydrology." *Current Opinion in Environmental Science & Health* 21: 100252.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Robichaud, Patrick J. L. and Julie C. Padowski 2024. "Drinking Water Under Fire: Water Utilities' Vulnerability to Wildfires in the Pacific Northwest." *JAWRA Journal of the American Water Resources Association* 60 (2): 590–602. https://doi.org/10.1111/1752-1688.13174.