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ORIGINAL RESEARCH

AWWA WATER SCIENCE

The Marshall Fire: Scientific and policy needs for water system disaster response

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Abstract

The 2021 Marshall Fire was the costliest fire in Colorado's history and destroyed more than 1,000 homes and businesses. The disaster displaced over 40,000 people and damaged six public drinking water systems. A case study was developed to better understand decisions, resources, expertise, and response limitations during and after the wildfire. The fire caused all water systems to lose power. Power loss was sometimes coupled with structure destruction, distribution depressurization, and the failure of backup power systems. These consequences jeopardized fire-fighting support and allowed for volatile organic compound and semi-volatile organic compound contamination of water distribution systems. Water system staff, with help from neighboring systems and external technical experts, stabilized the infrastructure, found and removed the contamination, and restored services. Actions were identified for utilities, governments, and researchers that could help communities minimize wildfire impacts, better protect workers and the population, and enable water systems to more rapidly respond and recover.

KEYWORDS

emergency, odor, VOC, water quality, wildfire

1 | INTRODUCTION

Globally and within the U.S., wildfires can cause public health and safety risks, and are increasing in intensity as well as the number of acres burned (UNEP, 2022; USGCRP, 2018; Westerling, 2016). The wildland urban interface (WUI), where human development meets and intermingles with vegetative and wildland fuels, is the fastest-growing land use (Clark et al., 2022; ICC, 2021). In the U.S. more than 46 million residences in 70,000 communities are at risk (USFA, 2022). Wildfires cause hundreds of millions of dollars of property damage each year (Ahrens, 2018), and public drinking water systems that serve these communities are vulnerable to damage.

Utility assets above and below ground are vulnerable to fires. In 2022, the Hermits Peak/Calf Canyon wildfire, the largest fire in New Mexico's history, prompted boil water advisories for 15 public water systems (NMDEM, 2022). Direct fire damage was found at water source infrastructure, tanks, pumps, service lines, and customer properties (Martinez, 2022). Also found were indirect impacts such as power line damage and destruction, power loss, depressurization, water main breaks due to water hammers from firefighting activities, and increased consumption due to customers working to protect their property. Loss of water pressure can jeopardize fire-fighting activities (AWWA, 2022; AWWA, 2018). Loss of water production, coupled with firefighting demands, leaks in distribution systems, and building plumbing can prompt pressure loss (Glazer et al., 2021; Grigg, 2003). Drinking water system contamination is also possible (Proctor et al., 2020; Sham et al., 2013). During recovery, the lack of safe water can cause businesses to close, financial hardships on households, residents to leave the area, and mental health impacts (Odimayomi et al., 2021).

Article Impact Statement
Actions were identified that could help communities minimize wildfire impacts, better protect workers and the population, and enable water systems to more rapidly respond and recover.

In recent years, U.S. wildfire policy has begun to change after widespread drinking water chemical contamination was discovered in California and Oregon (USEPA, 2021; USFEMA, 2019). Historically, coliform bacteria and surface water contamination were the main drinking water concerns (Hohner et al., 2016; Hohner et al., 2019; MWD, 2003; Pennino et al., 2022; Rorasio-Ortiz et al., 2018; Sham et al., 2013; Steninger, 2013; USCDC, 2022; Waskom et al., 2013). Since 2017, however, volatile organic compounds (VOC) have been found in 12 water distribution systems at levels above short- and long-term safe drinking water exposure limits (Tables 1 and 2) (Odimayomi et al., 2021; Proctor et al., 2020). For these events, contamination did not originate from a failure of the water treatment plants to adequately treat source water but entered the distribution systems directly. Semi-volatile organic compounds (SVOCs) can also be generated due to thermal damage to plastics and the combustion of structures and vegetation. SVOCs have also been found in surface waters after wildfires. Chemical distribution system contamination has been theorized

TABLE 1 Since 2017 water distribution systems have been chemically contaminated with benzene and other chemicals due to wildfires.

Conc., μg/L	Event/location	Population	System name	Year
5.5	Echo Mountain Fire/Oregon	120	Whispering Pines Mobile Home Park	2020
11.3	Echo Mountain Fire/Oregon	362	Hiland WC - Echo Mountain	2020
1.1	Echo Mountain Fire/Oregon	760	Panther Creek Water District	2020
76.4	Almeda Fire/Oregon	6,850	City of Talent	2020
44.9	Lionshead Fire/Oregon	205	Detroit Water System	2020
1.8	CZU Lightning Complex Fire/California	1,650	Big Basin Water Co.	2020
42	CZU Lightning Complex Fire/California	21,145	San Lorenzo Water District	2020
>2,217	Camp Fire/California	26,032	Paradise Irrigation District	2018
38.3	Camp Fire/California	924	Del Oro Water Co.-Magalia	2018
8.1	Camp Fire/California	1,106	Del Oro Water Co.-Lime Saddle	2018
530	Camp Fire/California	11,324	Del Oro Water Co.-Paradise Pines	2018
40,000	Tubbs Fire/ California	175,000	City of Santa Rosa	2017

Note: More VOCs were detected in these damaged water distribution systems and SVOCs were also screened in a few distribution systems and were detected. Only benzene water testing results were shown for brevity.

TABLE 2 List of volatile organic compounds (VOCs) detected in previous water distribution systems contaminated by wildfires since 2017

Acetonitrile	Chlorodibromomethane	Ethyl-*tert*-butyl ether (ETBE)	1,2,4-Trichlorobenzene
Acetone	Chloromethane	Iodomethane	1,1,1-Trichloroethane
Acrolein	4-Chlorotoluene	Isopropylbenzene	1,1,2-Trichloroethane
Acrylonitrile	Dibromochloromethane	**Methylene chloride	Trichloroethylene
**Benzene	1,2-Dichlorobenzene	**Methyl ethyl ketone (MEK)	Trichloromethane
Bromochloromethane	1,4-Dichlorobenzene	Methyl isobutyl ketone (MIBK)	1,2,4-Trimethylbenzene
Bromodichloromethane	1,1-Dichloroethane	**Methyl-*tert*-butyl ether (MTBE)	1,3,5-Trimethylbenzene
Bromoform	1,2-Dichloroethane	**Naphthalene	**Vinyl chloride
n-Butylbenzene	1,1-Dichloroethene	**Styrene	*ortho*-Xylene
sec-Butylbenzene	*cis*-1,2-Dichloroethene	***tert*-Butyl alcohol (TBA)	*meta*-Xylene
tert-Butylbenzene	*trans*-1,2-Dichloroethylene	Tetrachloroethylene	*para*-Xylene
Carbon disulfide	1,2-Dichloropropane	**Tetrahydrofuran (THF)	
Carbon tetrachloride	Ethanol	**Toluene	
Chlorobenzene	Ethylbenzene	1,2,3-Trichlorobenzene	

Note: Asterisk (**) indicates chemicals found exceeded short- or long-term drinking water exposure limits after past fire events; Results shown are limited by the analytical methods applied and are not comprehensive of all possible contaminants that could be present post-fire that pose a health risk.

to originate from (1) particulates and vapors drawn through damaged and open assets and/or plumbing during depressurization, and (2) thermal degradation of infrastructure components (service lines, meters, valves, gaskets, etc.) and direct leaching (Proctor et al., 2020). Previous investigators have shown that plastics can be a direct contamination source (Draper et al., 2022; Isaacson et al., 2021). Even if not thermally damaged, certain plastics can also be an indirect contamination source as they uptake contamination and leach it out slowly over time (Haupert & Magnuson, 2019; Huang et al., 2017; Whelton, Dietrich, & Gallagher, 2017; Whelton, McMillan, et al., 2017). After the 2020 CZU Lightning Complex Fire, a utility found that VOC contamination entered their storage tank vent pipes and contaminated the tank's epoxy interior lining, which had to be removed and replaced (Hagemann, 2021a). Benzene contamination has been correlated to the density of damaged and destroyed structures (Schulze & Fischer, 2021). Contamination is thought to spread to unaffected areas due to fire-fighting water demands, customer demands (i.e., sprinkler systems), and pipe breaks. After some fires, contamination has prompted damaged asset replacement (i.e., water mains, pipes, meters, tank linings), with significant financial costs. Following the 2018 Camp Fire, the damaged 172-mile water distribution system cost $150 million to repair, and after the 2017 Tubbs Fire, the repair of 5.2 miles of a water distribution system cost approximately $8 million (Becker, 2020; Walton, 2019). In 2020, the CZU Lightning Complex Fire damage to the source, treatment, and distribution system infrastructure was $20 million (Hagemann, 2021b).

A review of scientific, industry, and government documents revealed that national and industry approaches for water system contamination response to wildfires do not exist. Lessons from extreme weather events have been documented in recent years with a focus on source water, water treatment plant impacts, as well as power and pressure loss (Becker et al., 2018; Khan et al., 2015, 2017). Little guidance, however, is available to aid water utility staff decision-making when it comes to water distribution system damage and chemical contamination. This lack of information inhibits broader preparation, mitigation, response, and recovery decisions. Lack of guidance also hinders health officials and government agencies seeking to provide assistance and developing regulatory frameworks to protect public health. It remains unknown:

- How can neighboring water systems and external experts support the response?
- What conditions can prompt a utility to pump untreated water into its water distribution system to support fire-fighting operations?
- What challenges are encountered when designing and executing post-wildfire chemical water distribution system sampling and analysis plans?
- What circumstances are encountered when communicating health risks to customers?
- What approaches can help rapidly pinpoint the source of odd tastes and odors in the water?
- What actions can a primacy agency take to protect customers and the water system?

This study was conducted in response to the December 2021 Marshall Fire, one of the most expensive 2021 disasters in the U.S. (USNOAA, 2022) and the costliest fire in Colorado's history, exceeding $2 billion in losses (RMIIA, 2022). The study goal was to better understand decisions, resources, expertise, and response limitations during and after the wildfire. The specific objectives were to (1) Describe key events during the first 24 h of the response; (2) Review water utility sampling results and actions conducted over the next four weeks including key response and recovery phase challenges; and (3) Identify scientific and policy knowledge-gaps that inhibited better prevention and response. Results of this work were intended to assist the water, public health, and government sectors improve their decision-making process before and during incident response and recovery.

2 | MARSHALL FIRE INCIDENT OVERVIEW AND CASE STUDY APPROACH

2.1 | Incident overview

On the morning of December 30, 2021, two grass fires ignited in Colorado during a high wind event (BCS, 2022; CDHSEM, 2022). The Middle Fork Fire was extinguished after reaching 40 acres whereas the Marshall Fire continued to grow. At 11:00 a.m., sustained high winds (70 mph) and gusts (100 mph) spread the Marshall Fire quickly from Marshall Road in Boulder County into the town of Superior (USNWS, 2021). Within 2 h, more than 40,000 people were ordered to evacuate from the area. At 5:00 p.m. the fire had grown to approximately 1,600 acres (BOEM, 2021a) and increased to 6,219 acres by 10:00 a.m. the next day (BOEM, 2021b). On December 30, Governor Polis issued a state of emergency (OG, 2021). During the afternoon of December 31 and into January 1, snowfall helped contain the fire. A total of 1,084 structures were destroyed and 149 were damaged across Louisville, Superior, and unincorporated Boulder County (BC, 2022) (Figures SI-1 and SI-2). On January 1, 2022, President Biden declared the event a federal disaster (OWH, 2022).

The Marshall Fire was within the region of Boulder County where wildfires have historically not occurred (Figure SI-1) and impacted communities that differed significantly from the national average and others impacted by recent fires (Tables SI-1 and SI-2). The area impacted was home to more than 130,000 residents in Louisville, Superior, Lafayette, Broomfield, as well as unincorporated Boulder County. Geographically, the fire footprint was located four miles from the city of Boulder and 26 miles from the state capital, Denver. The median household income was roughly twice the national average (Louisville: $127,292/yr) and the community impacted had roughly twice the proportion of residents with a bachelor's degree or higher level of education than the national average (76.3%) (Table SI-1). The median home value in Boulder County was also roughly double the national average ($217,500 vs. $576,800). For comparison, the communities impacted by major wildfires in California and New Mexico were quite different [average income $37,500 to $49,000; bachelor's degree or higher level of education 17.1% to 32.5%] (Table SI-2).

2.2 | Public water systems impacted

Six public water systems were impacted by the Marshall Fire, and not all systems had assets that were fire damaged or chemically contaminated (Table 3). Louisville, Superior, and Lafayette water systems served the greatest number of people (about 66,000), while the other three systems served a combined total of fewer than 750 people. Each system's source, treatment, and distribution system infrastructure is described in the SI. Unlike the small water systems, the larger water systems had full-time staff onsite.

2.3 | Case study approach

The authors contacted a variety of organizations involved in water system response and recovery (Table 4). All authors engaged with Superior and Louisville, and the first joint onsite meeting occurred January 4, 2022. While onsite the authors met with utility staff, visited the areas impacted, inspected damaged water sources, treatment facilities, distribution assets, and customer properties, and assisted the municipalities with developing drinking water infrastructure damage and contamination assessment strategies. Some authors met with representatives of Lafayette, East Boulder County Water District (EBCWD), Sans Souci Mobile Home Park (SSMHP), and Eldorado Artesian Spring public water systems. Some authors also met with the Boulder County Health Department (BCHD), Colorado Department of Public Health and Environment (CDPHE), U.S. Environmental Protection Agency (USEPA) Regions 8 and 9, and community members. To compile this case study, water sampling, and testing records, public announcements, and meeting recordings were reviewed, along with sampling and analysis plans. In particular, the authors were involved in the development of some of these materials, sample collection, and data interpretation.

TABLE 3 Comparison of public water systems impacted by the Marshall fire

		Properties impacted by the fire			Water infrastructure			
System name (population)	Customer types	Destroyed	Damaged	Total impact on the community	Length of water main, miles	Number of hydrants	Water storage per tank, MG	Raw water sources
Louisville (20,319)	R/C/I	554	57	611 of 7,339	120	1,200	2.0 3.0 3.5	South Boulder Creek Marshall Lake, Harper Lake, Louisville Reservoir, Gross Reservoir, Carter Lake
Superior (17,170)	R/C/I	381	72	453 of 3,650	50	430	1.4 1.5 0.5	Carter Lake, Marshall Lake
Lafayette (28,700)	R/C	18	0	18 of 9,700	177	900	4.0 4.0 4.0 2.0	Baseline Reservoir, Goosehaven Reservoir
East Boulder County Water District (300)	R	72	0	72 of 137	8	40	0.1	City of Lafayette interconnection
Eldorado Artesian Spring, Inc. (259)	I	nr	nr	nr	nr	nr	nr	2 Wells, 1 Spring
Sans Souci Mobile Home Park (150)	R	0	3	3 of 61	<1	None	None	1 Well

Note: R: Residential, C: Commercial, I: Industrial; Damaged properties at SSHMP were affected by wind, not heat or fire; Service population data were obtained from the federal Safe Drinking Water Information System database in January 2022; nr: not reported; Data on destroyed and damaged homes from BC (2002).

3 | RESULTS AND DISCUSSION

3.1 | The first 24 h: Water pressure, power, and water loss

During the first 24 h, each water system sustained damage, and the most detailed response information was available from the larger water systems (Figures 1 and 2). Superior was the first large system to be impacted as the fire moved from West to East (Figure SI-3). The fire then entered Louisville and then part of Lafayette. Of the large systems, Lafayette had the least number of buildings destroyed and water infrastructure assets damaged.

Water utility staff indicated that many decisions were driven by water pressure reductions and water loss due to structure damage. Superior was unable to provide water to their distribution system during the fire because the electric power supply was lost and natural gas was shut off to their sole water treatment plant (WTP). This would not necessarily have prompted an immediate concern, but Superior's WTP backup generator was also destroyed by the fire. To assist Superior, Louisville opened its interconnection and delivered 1 million gallons of water per day (MGD) and pressure. However, as the fire spread, Louisville's water distribution system also encountered pressure and water loss as the number of structures destroyed increased. Low pressure in Louisville was first detected by fire-fighters at fire hydrants because telecommunication with assets was lost (Fischer, Wham, Dashti, et al., 2022a). Unlike Superior, which only had one WTP, Louisville had two WTPs. Their northern WTP was located outside the fire footprint and provided supply throughout the fire. During the fire, the utility also worked to startup their seasonal southern WTP. However, the southern WTP was unable to start due to the absence of electrical power, and the natural gas was shut off by the service provider in response to the fire. To support Louisville, Lafayette began sending 1.5 MGD into the water distribution network via a hydrant-to-hydrant connection with a backflow preventer. Lafayette did not lose water pressure, and for a few minutes lost power at its booster station but their diesel emergency generator

TABLE 4 Organizations involved in incident response and recovery

Name	Role
Colorado Department of Public Health and Environment (CDPHE)	*Safe Drinking Water Act* primacy agency for public water systems; Issued and lifted boil water advisories and a bottled water advisory; Provided technical assistance to public water systems; Reviewed and approved testing and recovery plans; Participated in a public meeting with Superior about the cause of off–taste and –odor in Superior; Issued cross-connection control guidance; Provided BCPH guidance on private drinking water well owner testing.
Boulder County Public Health (BCPH)	Responsible for the physical and mental health of citizens in the county; Provision of guidance to private well and septic system owners.
Public water systems	
Town of Superior	Municipality and public water system owner; Water system operations contracted to a third party.
City of Louisville	Municipality and public water system owner and operator.
City of Lafayette	Municipality and public water system owner and operator.
East Boulder County Water District (EBCWD)	Public water system owner; Water system operations contracted to a third party.
Sans Souci Mobile Home Park (SSMHP)	Public water system owner and operator
Eldorado Artesian Springs, Inc.	Public water system owner and operator.
Xcel Energy	Natural gas and electric power suppliers for the communities impacted by the fire.
The authors	
Purdue University	Provided technical support to the city of Louisville, town of Superior, city of Lafayette, EBCWD, SSMHP, CDPHE, BCPH, and private well owners.
University of Colorado	Provided technical support to the city of Louisville, town of Superior, and EBCWD.
Oregon State University	Provided technical support to the city of Louisville and the town of Superior.
Corona Environmental Consulting, LLC	Provided technical and logistical support to the city of Louisville and the town of Superior.
US Environmental Protection Agency (USEPA)	*Safe Drinking Water Act* executive agent who designated the CDPHE as the primacy agency; Provided technical support to the CDPHE.

was restored to power. One of Lafayette's pump stations lost electrical power, which shut off the building's heating system. Coupled with the cold air temperature, a pipe froze, burst, and flooded the pump station.

Understanding pressure and water storage levels within the distribution system was a challenge for Superior and Louisville. Loss of communication with infrastructure and concerns about low pressure prompted Superior and Louisville staff to drive to storage tanks and estimate water loss. For example, during Louisville's storage tank inspections, staff reported that about 1 to 2 ft of water remained (8% to 12% of their total volume). While in the field, Louisville staff estimated that with 300 to 400 homes destroyed, they were losing 6.5 MGD to 12 MGD, roughly 50% to 90% of the water they were producing. Even with both North and South WTPs combined their system production capacity was only 13 MGD. In response, Louisville closed the interconnection with Superior and then opened valves to send untreated lake water into their distribution system to support firefighting activities. Later that evening, power was restored to the South WTP after Xcel Energy drove a 9,300-gallon liquefied natural gas truck into the active fire zone to provide temporary service. To further stem water loss, Superior, Louisville, and Lafayette utility staff closed curb stops, water meter yokes, and valves serving subdivisions to damaged and destroyed properties and sometimes removed water meters.

Less information was available about actions taken by the smaller water systems during the first 24 h. The EBCWD and SSMHP did not have facility evacuations because their part-time staff were not present. The EBCWD was located between Superior and Louisville and more than 50% of their customer properties were destroyed. The EBCWD received treated drinking water through an interconnection with Lafayette. During the fire, the distribution system lost pressure and many service lines were leaking. Power at the EBCWD's sole pump station was also lost; Their natural gas-fueled emergency generator could not run because Xcel Energy

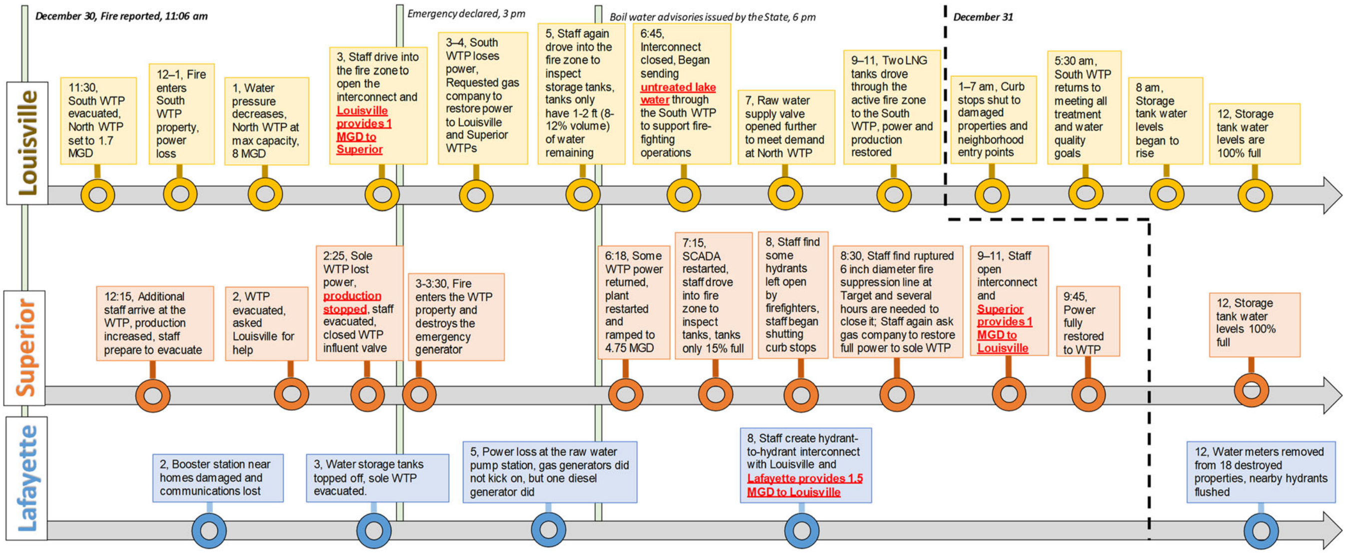

FIGURE 1 The first 24 h of the response challenged water system staff in different ways. By 8:00 a.m. on December 31, Louisville storage tank water levels began to rise and by noon, snow began to fall, the temperature dropped below freezing, and storage tank levels were full in Louisville and superior. At the same time, Lafayette removed water meters from destroyed properties and flushed hydrants. By January 5, 2022, electricity and gas services were restored to the majority of standing homes. Between January 4 to 6, boil water advisories were lifted by the Colorado Department of Public Health and Environment (CDPHE). Additional timeline details can be found in Fischer, Wham, Dashti, et al. (2022a).

shut off natural gas to the area. The SSMHP did not experience fire damage but instead, winds caused tree limbs to damage power poles and prefabricated homes. Plumbing at a few homes was found leaking after the fire, and water was shut off at service connections within the mobile home park. The SSHMP did not have power for four days and did not have a backup emergency generator, or a finished water storage tank. Information about the Eldorado Artesian Spring system was not available. Boil water advisories were issued by the CDPHE (2022a) for all six systems.

3.2 | Water quality sampling results and actions

3.2.1 | Reasserting disinfectant and bacterial control

After the fire was contained, all water systems first focused on damage assessment, flushing, and re-pressurizing their water distribution systems. All systems flushed water to the ground or storm drains. For Superior and Louisville, water mains were flushed by opening hydrants progressing from the WTPs to the distal ends of each system. In Louisville, this action also focused on removing untreated lake water which was located in one of the three pressure zones. For both systems, chlorinated water was flushed through the distal ends of the distribution networks and pressure was restored to service areas that had not been hydraulically isolated from the main distribution system. During this time, chlorine disinfectant levels exiting the WTPs were increased to 3 to 4 mg/L as Cl_2. Typically, system-wide flushing of the Superior and Louisville systems required four to six weeks, but mutual aid from neighboring water systems enabled complete flushing within four days working 24 h a day. More than 30 people from neighboring communities of Erie, Lafayette, Boulder, Westminster, Longmont, and South Adams County Water helped with flushing operations. Because Lafayette only had 18 homes destroyed, after water utility staff closed water meter yokes, their property service lines were left stagnant for three weeks. At the EBCWD, hydrant flushing was conducted by their part-time contract operator at a few distal hydrants and a Lafayette operator also flushed the Lafayette-EBCWD interconnection. At the highest service area elevations, 100 ft above the rest of the system, the EBCWD operator flushed air from hydrants for 2 h (SI). Flushing actions at SSMHP and Eldorado Artesian Springs were not reported to the authors.

To ascertain the microbiological condition of water distribution systems, the state drinking water primacy agency required coliform and disinfectant residual sampling (Figure SI-4). When no coliform contamination was found, the agency lifted the boil water advisories and directed building owners to guidance on how to flush and replace plumbing items (CDPHE, 2019; CDPHE, 2022g). Water billing credit was not provided to customers who

FIGURE 2 Water systems experienced different degrees of damage as service lines, hydrants, and property plumbing were damaged and leaking, and source water and treatment and facilities were also impacted.

flushed their plumbing in Superior, EBCWD, or Lafayette. Louisville voided all utility bills in January 2022 (including water) so that customers could flush their plumbing at no cost. On February 11, Louisville issued a public notice about their WTP's loss of power and the pumping of untreated lake water in their distribution system during the fire (City of Louisville, 2022).

3.2.2 | Sampling, detecting, and removing organic contaminants by flushing

Some VOCs found in water distribution systems after wildfires in California and Oregon were found in the Louisville and EBCWD systems. Two weeks after the fire, Louisville began to focus on assessing damage to the hydraulically isolated parts of its water distribution system. There, first draw samples were collected followed by flushing, sample collection, a 72 h stagnation period, and then another sample collection. This practice also helped utilities in California and Oregon find contamination (OHA, 2020; Proctor et al., 2020; Whelton et al., 2019). In Louisville, VOC contamination was found above short- and long-term drinking water exposure limits (Table 5), though the majority of water samples collected had no VOC detections. VOC concentrations were greatest for the initial stagnation period and decreased during weeks of water main and service line flushing. More than 60 VOC water samples were collected by Louisville before VOCs exceeding drinking water limits were detected. This was likely due to the prior samples being collected in areas with minimal property damage, flushing, and unrestricted water use. Several tentatively identified VOCs were reported by the only laboratory that screened for them (Table SI-3). Some VOCs exceeded odor threshold limits and state-specific drinking water screening

TABLE 5 List of 15 volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) found with the highest concentrations in the isolated part of the City of Louisville's water distribution system where contamination was found.

		Exceedances of drinking water limits			Percent of detections above the method detection limit (MDL) and MCL		
Chemical	**Type**	**USEPA health advisory/ other**	**USEPA MCL**	**Odor**	**>MDL, %**	**>MCL, %**	**Maximum concentration detected**
Styrene	VOC	20,000	**100**	Yes	7.7	1.4	1,900
Toluene	VOC	20,000	1,000		11	0	512
4-Chloro-3-methyl phenol	SVOC	*2,000	–		3.9	0	320
Benzene	VOC	**200/26**	**5		10	2.6	221
Ethanol	VOC	nr	–		0.2	0	220
Ethylbenzene	VOC	30,000	700		12	0	160
Chloroform	VOC	4,000	–		99	0	97
Benzyl alcohol	SVOC	*2,000	–		5.3	0	48
Acetonitrile	VOC	nr	–		0.2	0	36
Acrylonitrile	VOC	*200	–		0.2	0	31
Acetone	VOC	*18,000	–		7.7	0	30
1,2-Dichlorobenzene	SVOC	9,000	600		11	0	29
2,6-Dinitrotoluene	SVOC	***6**	–		0.3	0	25
Acrolein	VOC	***10**	–	Yes	0.2	0	24
Benzaldehyde	SVOC	*2,000	–		21	0	23

Note: All results reported as μg/L; Bolded results indicate a short- or long-term drinking water exposure limit was exceeded; Results represent January 1 to February 9, 2022; USEPA short-term exposure period represents the 1 day health advisory; Asterix (*) indicates a USEPA health-based Regional Screening Level value; (nr) indicates compound does not have a USEPA screening level, health advisory or MCL; Naphthalene exceeded its odor limit but was not one of the 15 most detected contaminants; With the exception of benzaldehyde (62), all contaminants shown represent 357 to 511 water samples. Other VOCs and SVOCs were detected and these results can be found in the SI file.

levels. Due to logistical challenges, water sampling for SVOCs was not conducted until three weeks after the fire. The minimal number of samples collected did reveal 55 SVOCs were present (Table SI-4), and none exceeded health-based drinking water limits.

To remove contamination, water was flushed through hydrants, blow-off valves, and service lines, but contamination in Louisville remained at select locations above the benzene maximum contaminant level (MCL) for weeks. For example, hydrant water samples collected at the end of one street in Louisville revealed benzene above its 5 μg/L MCL (Figures SI-5, SI-6, and SI-7). Benzene was also found in a nearby damaged home's service line above 5 μg/L, but service line flushing for 5 min decreased the concentration to less than 0.5 μg/L. Benzene was initially detected below the MCL in the nearby standing home's service line but was not detected upon flushing and re-sampling after the 72 h stagnation period. Eight weeks later, benzene was detected again in a stagnant sample from the nearby water main at 0.65 μg/L, but benzene was not detected in the flushed water sample. Broadly, results indicated that repeated sampling of hydrants and service lines was needed to find contamination, and confirm flushing was reducing the contamination. Three months after the fire Louisville no longer detected contamination in its distribution system. Though, like other wildfire-impacted water systems in other states, Louisville continued to conduct VOC surveillance monitoring in their distribution system. Similarly, after the 2017 and 2018 Tubbs Fire and Camp Fire in California, VOC detections in water distribution systems were found more than nine months after the fires (Proctor et al., 2020). Also after the Camp Fire, one water utility chemically analyzed water from the water main to the water meter buried in front of the structure. After the Marshall Fire, Louisville instead sometimes sampled water drawn from customer faucets or from the service line entering the basement because many of the water meters were located in customer basements.

VOC water distribution system sampling was also conducted by Superior, EBCWD, and Lafayette and only the EBCWD found contamination. Superior conducted sampling in January (38 samples) and early February (30 samples) for wildfire-associated VOCs using two different laboratories (Town of Superior, 2022). Many samples were collected without stagnation. For service lines, Superior collected water samples by disconnecting water meters buried in front of each home, installing a jumper for the yoke, and a nozzle or spigot on the service line to collect a sample.

Four weeks after the fire, some authors conducted an onsite visit with the EBCWD (SI). At that time, the authors learned that a few VOC samples had been collected five days after the fire, but those samples represented flushed water, not the stagnant "paint thinner odor" water a customer had complained about. In response to this onsite visit and discussions with the CDPHE, the EBCWD conducted follow-up sampling and first draw samples contained 0.8, 1.0, and 5.8 μg/L benzene along with detectable levels of ethylbenzene, ispropylbenzene, naphthalene, styrene, toluene, and total xylenes. No contamination was detected for flushed water samples. The array of chemicals initially present and their maximum concentrations remain unknown because: (1) water use was permitted without adequate chemical testing during and after the boil water advisory, and (2) flushing was conducted with inadequate chemical testing.

In early February, Lafayette conducted a VOC sampling of 18 pressurized property service lines at the water meters buried in the front of the destroyed homes. To collect water samples "candy cane" rigs were manufactured and utilized (Figure SI-8). The service lines sampled had remained stagnant for three weeks after their water meters were removed. First draw water samples were collected and additional samples were collected after flushing each service line for 2 min. No wildfire-related VOCs were detected in any water sample. Unlike the Louisville and EBCWD distribution systems where portions were depressurized, Lafayette's network remained under positive pressure during the fire.

3.3 | Drinking water taste and odor issues in the Town of Superior

After the fire, Superior experienced an abundance of customer complaints and concerns about water odor, whereas the other water systems affected did not. On average, Superior received five drinking water complaints per year. Once the CDHPE lifted the boil water advisory in Superior, 21 complaints were filed over six days. These complaints pertained to cold and hot water having faint, smoky, chemical, and VOC-like taste and odor characteristics. To better understand the reason for the complaints, Superior asked customers to formally email or call in their concerns, which prompted 296 complaints over two days (Figure SI-9). Complaints primarily pertained to taste and hot water-related smoky and ashy odors. In summary, residents commonly reported that off-flavors (1) remained even after draining their water heaters and flushing their plumbing multiple times, (2) odor was only in hot water and not in cold water, and (3) odor was in both cold and hot water. One customer reported replacing their water heater and some reported flushing their plumbing every day to remove the odor. From a public health perspective, there was an initial concern that chemicals present may have entered the water distribution system due to depressurization. Monitoring customer feedback has previously been shown to provide valuable information about distribution system integrity (McGuire et al., 2014; Whelton et al., 2007). When customer concerns were initially reported, Superior had limited VOC water testing data.

To address the off-flavor concerns, Superior teamed with Corona, the University of Colorado, and Colorado State University (Town of Superior, 2022). Sensory testing confirmed that the smoky flavor was present in the source, treatment plant, distribution system, and customer fixtures even when chlorine residual was present (Omur-Ozbek, 2022). Chemical analysis revealed benzene-1,2,3-tricarboxylic acid (boiling point 491°C) and 1,4-benzendicarboxylic acid (boiling point 392°C) were the likely "smoky flavor" agents at μg/L levels (UCB, 2022). These compounds were previously identified to cause smoky odors elsewhere (Ferrer et al., 2021). Superior and Corona concluded that the chemicals were not known to be a health risk at the levels found, and posed only an aesthetic issue. Prior researchers have also identified multiple compounds producing these off-flavors (Fiddler et al., 1970) such as phenols, *o*-, *p*-, *m*-cresols, and guaiacol (Fudge et al., 2012; Kennison et al., 2008; Kostyra & Baryko-Pikielna, 2006; Parker et al., 2012). Seven months after the fire, a community survey revealed that Superior customers had lower confidence in the safety of their drinking water than before the fire (Table SI-5) (Dickinson et al., 2022; MFRRWG, 2022).

3.4 | Cross-connections between damaged and destroyed buildings to the water distribution systems and decontamination

It is known that distribution system pressure loss can draw water from property plumbing into the distribution system and create health risks (Casteloes et al., 2015; Hrudey & Hrudey, 2014). Some utilities physically removed water meters from damaged properties to prevent contamination from being drawn back into the distribution system. In Lafayette, meters were removed from all damaged properties and curb stops as well as other components were closed. In Superior and Louisville, meters were often located in basements, and debris prevented curb-stop access. Also complicating the isolation process was that some properties in Superior had a leaking or lacked a curb stop altogether. Because some finished water tanks exhibited wind damage, and vent pipes and ash may have been drawn inside, Superior and Louisville drained, inspected, and cleaned these assets. The small system EBCWD did not remove water meters until one month after the fire when their VOC contamination investigation was initiated (SI).

To address the cross-connection public health concern, the CDPHE sent formal notices six weeks after the fire to Louisville (CDPHE, 2022b), Superior (CDPHE, 2022c), Lafayette (CDPHE, 2022d), and the EBCWD (CDHPE, 2022e). This notice provided guidance to the public water systems regarding the protection of their water distribution systems from damaged and destroyed buildings. Specifically, the CDPHE invoked Colorado Primary Drinking Water Regulations, 5 CCR 1002–11 (Regulation 11), Section 11.39(3) (b), which required that water systems notify and consult them about backflow contamination (CDPHE, 2017). To expedite recovery, the CDPHE provided the systems with three options to achieve compliance (Box 1). The importance of this action is exemplified by an incident pertaining to the EBCWD. When the EBCWD removed water meters one month after the fire, its staff discovered that one property owner had reopened their shut-off water meter without permission thereby connecting their damaged property to the water distribution system.

BOX 1 Options that the CDPHE provided to public water systems to achieve compliance with backflow prevention requirements after the Marshall Fire

1. Perform appropriate water quality sampling at the fire-impacted connection to ensure that no contaminants are present in the potable water supply. Please consult with the department for appropriate sampling requirements.
2. Install an appropriate backflow prevention assembly at a non-impacted location to control the connection. The supplier must ensure that all installed backflow assemblies are tested by a certified cross-connection control technician upon installation. If a previously installed backflow assembly is suspected of being impacted by the fire, the assembly must be retested in order to confirm the connection is controlled.
3. Replace all water supply infrastructure, including the meter pit and the entire service line. If all water supply infrastructure has been replaced, the supplier can follow normal protocols for supplying water to a new connection.

3.5 | Estimated water system expenses as of 11 months after the fire

No detailed financial analysis of wildfire-impacted utilities was found in the literature, but expenses associated with the fire were reviewed in the present case study (SI). Louisville, Superior, Lafayette, and the EBCWD sought expense reimbursement from their insurance companies and the FEMA. For the large water systems, Superior reported the greatest total cost associated with water system response and recovery of $4,643,000. Louisville's estimated expenses were $1,440,000, and Lafayette incurred about $60,000 in expenses. Not included in Louisville's estimated expense was an $827,000 revenue loss because the city voided all customer utility bills (potable water, sanitary sewer, storm sewer, and trash) for the month of January 2021. The majority of Superiors' expenses (81.8%) were attributed to characterizing, evaluating, and operating new water treatment systems for their reservoir which became contaminated with SVOCs.

Costs encountered by the water systems were associated with system shutdown and restart, distribution system water sampling and analysis, additional operations and maintenance labor, asset inspections and cleaning, system flushing, equipment, and asset repair and replacement, the cost of treating and providing emergency water to the neighboring utility through interconnection, and the purchase and provision of bottled water to impacted customers. At the time this case study was finalized, insurance had not reimbursed water systems for all costs and several claims were in progress. In Louisville's case, no reimbursement had been received. All water systems relied on their cash reserves to financially support disaster response and recovery while waiting for insurance and FEMA reimbursement claims to be considered. Because the water system recoveries are continuing, costs are expected to continue to increase.

4 | LESSONS LEARNED ACROSS PUBLIC WATER SYSTEMS

All public water systems impacted were in compliance with federal water system emergency response planning

TABLE 6 Scientific and policy needs for improving water system disaster response and recovery

Recommendations	Proposed responsible groups
1. Obtain wildfire-specific personal protective equipment (PPE) and train utility staff on how to prevent injuries.	Utility
2. Acquire or identify backup emergency generators so that a power loss lessens the chance pressure loss occurs, fire-fighting support is jeopardized, and distribution system contamination occurs.	Utility
3. Establish mutual aid agreements for personnel to assist in system repair, water sampling, analysis, and equipment access enabled through the Water/Wastewater Agency Response Network (WARN).	Utility
4. Install physical interconnections with neighboring utility distribution systems to support emergency pressure and water needs.	Utility
5. Conduct department, organization, and multi-organization exercises to practice addressing the operational, managerial, scientific, and communication challenges during and following a wildfire.	Utility
6. Top off all finished water storage tanks in anticipation of an approaching fire, a power loss, or distribution system damage that can prompt water leaks.	Utility
7. Contact the state water testing laboratory and commercial laboratories to determine who guarantees to provide 24- to 72-h turnaround times for emergency post-fire sampling/analysis support.	Utility
8. Identify the conditions where untreated or partially treated source water would be sent into the water distribution system to support fire-fighting activities.	Utility, State
9. Upgrade distribution system construction requirements, such as pressure zone separations, service line backflow prevention devices, auto-shutoff meters/valves, and selective plastic use to reduce the rate and magnitude of pressure loss, water loss, and impact of chemical contamination.	Utility, State
10. After a fire, require water meter removal and the physical disconnection of damaged and destroyed properties from the water distribution system if no functional backflow prevention device exists.	Utility, State
11. Require chemical testing of the property service line, install a backflow prevention device, or replace infrastructure before damaged property services are reconnected to the distribution system.	Utility, State
12. As part of employee training and organizational culture, share experiences about responding to and recovering from disasters that impact water distribution systems.	Utility, State, and Federal
13. Establish and maintain relationships with subject matter experts on water distribution system contamination response and recovery actions, technical support, and decision making.	Utility, State, and Federal
14. Develop evidenced-based standard practices for post-fire VOC and SVOC water sampling and analysis for water mains, hydrants, blowoffs, storage tanks, service lines, and other infrastructure.	Research, State, Federal
15. Review state water testing laboratory capabilities and identify commercial laboratories that guarantee to provide utilities 24 h to 72 h turnaround time emergency post-fire sampling/analysis support. Share this with state agencies and utilities.	State, Federal
16. Investigate the conditions that prompt chemical contamination of distribution systems and locations where contamination becomes sequestered to better prevent and respond to the hazard.	Research
17. Identify the public health risks associated with short-term exposure to wildfire-contaminated water and develop evidence-based contaminated water use recommendations.	Research, Federal
18. Characterize VOC and SVOC fate in distribution networks that contain metal and plastic materials and also consider scales and biofilms.	Research
19. Conduct a risk tradeoff analysis for flushing chemically contaminated water from distribution systems to storm drains and the ground, focused on rapidly returning infrastructure to safe use.	Research, Federal
20. Conduct a financial impact study that considers water utility wildfire response needs, expenses, insurance, and reimbursement experiences. Also, quantify economic impacts on establishments such as schools and businesses that need clean water to provide service.	Research, State, Federal

Note: State organizations may include the *Safe Drinking Water Act* primacy agency and health departments; Federal organizations may include the USEPA and CDC.

requirements (US Congress, 2018), but several actions can improve water utility and state-level preparation, response, and recovery (Table 6). Based on the lessons from the present work, the literature, and the author's experience, the responsibility for each recommendation was assigned to one or more groups (Utility, State, Federal, and

Research). Recommendations pertained to worker safety and training, mutual aid, specialized technical assistance, system operations, public notification, water testing, decontamination, and water distribution system design. While not legally required, tabletop and field water emergency exercises should be considered to help utilities identify response questions and needs (Whelton et al., 2006; USEPA, Office of Water, 2012a, 2012b; Deere et al., 2017).

4.1 | The loss of interdependent utilities jeopardized the fire-fighting support mission and contributed to occupational risks for utility staff

During the fire, the lack of power to utility facilities and damage to customer properties threatened water availability for fire-fighting support. Wind, fire, and a subsequent snowstorm prompted more than 100,000 customers to lose electricity across the region. Natural gas was turned off for about 13,000 customers during the fire including multiple water treatment facilities. The absence of electric power and natural gas inhibited Superior, Louisville, and the EBCWD from maintaining water pressure in their distribution systems. These systems all had backup natural gas-powered emergency generators that could not be operated. Structure destruction further exacerbated water loss as each damaged structure became an uncontrolled water outflow. Power restoration enabled some systems to restart water production and begin to restore distribution system pressure. In the future, utilities should expect that as a wildfire approaches natural gas providers will shut off supply and the emergency generators should be designed to rely upon other fuel approaches (i.e., diesel).

Proper personal protective equipment (PPE) and training are needed for utility staff to help prevent injuries, illnesses, and other consequences from hazards and exposures associated with wildfires. Due to the lack of telecommunication with water storage tanks, utility staff drove into the active fire zone and climbed the tanks in high winds to estimate tank water levels. Staff also drove to destroyed and burning properties to shut off curb stops and water meter yokes. During travel, the staff encountered downed power poles, blowing debris, active fires, and high winds. Throughout these tasks, the staff did not have respirators and were not previously trained for understanding wildfire occupational hazards. Discussions with utility staff from outside Colorado at other fire-impacted water systems indicated that during wildfire responses utility professionals conducted similar activities, but also lacked formal training and PPE. Worker safety guidance for working in wildfire environments can be obtained from the National Institute for Occupational Health and Safety (USNIOSH, 2022). Certain states also have specific occupational safety requirements pertaining to wildfire smoke (CDIR, 2022; Oregon OSHA, 2022; WSDLI, 2022). To lessen the need for physical travel to infrastructure in an active fire zone, technology that enables remote asset shutoff (i.e., water meter, backflow prevention device) at each service line is recommended.

4.2 | Local and external utility resources helped expedite the response

The magnitude of the fire's impact and recovery exceeded the normal staffing capabilities of the utilities. No utilities were members of the Colorado Water/Wastewater Response Network, a mutual aid network where utilities help each other (COWARN, 2022). When asked for help, neighboring utilities provided staff and expertise to Superior and Louisville. Members of these neighboring utilities helped collect water samples, flush hydrants, shut curb stops, procured laboratories, and transport water samples to the laboratories. The smaller water systems had little to no assistance. Before a fire, cross-jurisdictional coordination and mutual aid agreements might enable smaller water systems to have access to onsite technical support similar to larger water systems. Lessons from regional disaster response resource planning, similar to earthquake preparation and other wildfire-impacted small water systems may be applicable.

Expertise in large water systems and the state was available to respond to depressurization and bacteria water safety concerns, but no Colorado entities had prior expertise specific to chemical water distribution system contamination by fire. Before week 2, some authors engaged the CDPHE and utilities to initiate a more detailed understanding of the potential damage assessment and recovery challenges post-wildfire. In week 2, Superior and Louisville engaged all of the authors. At the same time, the CDPHE also reached out for advice to the USEPA, Oregon Health Authority (OHA), and reviewed available studies and government documents (CSWRCB, 2019; Isaacson et al., 2021; Odimayomi et al., 2021; OHA, 2020; Proctor et al., 2020; USEPA, 2021; Whelton et al., 2019). Separately, small water systems primarily relied on part-time operators and the CDPHE for advice on post-fire system decontamination practices, sampling procedures, locations, and chemical analysis methods.

4.3 | Standard practices for sampling, analysis, and rapid external laboratory support are needed

Initial water safety determinations were slowed by water sampling, chemical analysis, and logistical challenges.

When the fire occurred, all utilities were not aware of what, where, and how to collect post-fire water samples. Further, utility staff should be educated about the sampling protocol nuances (i.e., sampling immediately after the fire, before flushing, and stagnation time). The need for educating utilities about this activity was revealed through experiences at the EBCWD. Five days after the fire, when a paint-thinner odor was reported to the EBCWD by a customer, the EBCWD operator collected one VOC sample after flushing out the paint-thinner odor water. That sample indicated no VOC contamination. But, the collection of first-draw samples and samples after stagnation had been previously shown to increase the chance of finding contamination (Haupert & Magnuson, 2019; Proctor et al., 2020). Follow-up sampling by the EBCWD weeks later, when stagnation was applied, revealed chemical contamination was present where benzene was 5.8 μg/L and other contaminants were below health-based drinking water limits (ethyl benzene, isopropylbenzene, naphthalene, styrene, toluene, xylenes). The lack of water stagnation during the early response in EBCWD prevented the discovery of chemical contamination. Early water sampling without stagnation in Superior and Louisville may have also prevented the early discovery of contamination in the distribution system where some damaged buildings and depressurization occurred. Where disaster debris was present and water meters were located in burned home basements, sampling water from service lines was nearly impossible.

A drinking water chemical analysis "fire package" was proposed during the Marshall Fire response (Figure 1), and should be revised as more VOC and SVOC data becomes available. A current limitation is that the list only includes VOCs laboratories chose to screen in past wildfires, not necessarily all VOCs and SVOCs that may have been present at levels of health concern in the contaminated water. More work is needed to identify which chemicals should be screened for in drinking water after a wildfire. Another issue with the "fire package" list is that previous laboratories have applied different drinking water chemical analysis methods across and even within neighboring water systems; Some laboratories chose to look for specific chemicals while others did not screen those compounds. SVOCs can also be present in surface water and water distribution systems after fires, but very limited distribution system testing has been conducted to date. Discussions with utilities and government agencies in and outside Colorado indicated that this is partly due to professionals not being aware SVOCs can be present, and the cost and time needed to analyze water for SVOC samples. Similar challenges have been encountered following chemical spills that contaminated water distribution systems and plumbing (Whelton, Dietrich, & Gallagher, 2017; Whelton, McMillan, et al., 2017). Additional work is needed to understand which VOCs and SVOCs are most likely present in drinking water and are at levels that pose a health risk. In light of limited data and the need to quickly identify chemicals of concern, water utilities and states should broadly characterize drinking water VOC and SVOC quality after wildfires.

A formal and rapid-response chemical testing laboratory support network is needed to support these disasters. Multiple water systems encountered great difficulty finding laboratories that could support their response. For Louisville alone, six commercial laboratories were contacted for assistance. Some laboratories did not respond to requests, lacked sampling supplies, and stated they could not promptly (less than five days) provide results to the water system. In week 2, some laboratories that had been assisting Louisville were unable to continue because of laboratory capacity constraints and prior client commitments. Different laboratories applied different EPA Methods (524.2, 524.4, and 8260C), and chose to quantify different chemicals when using the same method (Table SI-4). In week 3, SVOC water sampling was initiated in Louisville with EPA Method 8270E, but SVOCs were not analyzed in any other water system. Rapid turnaround times of less than 24 h could not be consistently met by any laboratory.

4.4 | Chemical contamination of the water distribution system seemed to be related to depressurization and property damage, but more work is needed

Post-fire chemical water sampling should be prioritized for areas where depressurization and property damage occur. Louisville and the EBCWD experienced depressurization and contamination of their water distribution systems. No VOC contamination was found in Superior's distribution system despite widespread building destruction and depressurization. Therefore, more work is needed to identify the factors associated with drinking water contamination due to fires. Standardized post-fire VOC and SVOC sample collection and analysis approaches would enable a more comparable assessment across water systems and fires. The fate of these contaminants in the distribution network involving plastic and metal infrastructure, scales, and biofilm, under myriad hydraulic and environmental conditions, should also be explored. A recent survey revealed that less than 20% of 24 Western U.S. municipalities had considered the threat of wildfires in water system pipe material selection decisions (Fischer, Wham, & Metz, 2022b). A better understanding of how infrastructure responds to heat, fire, and contamination is needed.

Evidence from the present study and prior fires indicates that properties with destroyed and even damaged structures should be physically disconnected to protect the utility infrastructure and other customers from cross-connection contamination. Before a fire occurs, backflow protection devices on service lines and preventative network zoning may help minimize the spread of chemical contamination. By isolating zones from one another, damage to one zone may not prompt pressure loss and contamination drawn into another. After the 2020 CZU Lightning Complex Fire in California, the San Lorenzo Valley Water District was able to contain the chemical contamination in one neighborhood partly because that portion of their water system was isolated as a separate zone.

4.5 | Clarification on public health risks and water use conditions is needed

Evidence from multiple wildfires suggests that clarification is needed on what conditions should prompt certain drinking water advisories. The *Public Notification Rule* requires that customer notification occurs within 24 h when drinking water situations have "significant potential to have serious adverse effects on human health as a result of short-term exposure." Public notification is meant to provide the customer with information about the contaminated water's potential chemicals, exposure pathways, adverse health impacts, and other information (USEPA, 2009). Past wildfires have shown VOCs (1,000s to 10,000s of ppb) can be present in distribution systems far exceeding short-term drinking water exposure limits. SVOCs can also be present. It is well-known that VOCs and SVOCs can pose inhalation, dermal, and ingestion exposure risks during bathing, cooking, appliance use, and other activities (Davis et al., 2016; Omur-Ozbek et al., 2016; Sain et al., 2015). Therefore, warning wildfire-impacted customers that the water may be contaminated and pose ingestion, inhalation, and dermal exposure risks is warranted. The absence of representative water testing data, in light of damage and depressurization, would indicate that a water system and state could not confirm the safety of the water.

Water use guidance issued in Colorado underscores a much larger public notification problem associated with wildfires. The boil water advisories were not designed to protect customers from being exposed to chemically contaminated water. Only Louisville urged their customers to avoid drinking and contact with water as they conducted sampling and ultimately found contamination (SI). Because of inadequate testing, the EBCWD discovered chemical contamination in their system weeks after the CDHPE's Boil Water Advisory was lifted. While the CDPHE required the EBCWD to issue a Bottled Water Advisory after discovering contamination, the lack of adequate data inhibited prior water use decisions (CDHPE, 2022f; EBCWD, 2022). In California and Oregon, water utilities and state agencies have also encouraged their customers to boil their water which turned out to be chemically contaminated (City of Phoenix, 2020; City of Santa Rosa, 2017a; City of Talent, 2020; PID, 2018a). Sometimes, but not always, utilities issued Do Not Drink-Do Not Boil warnings to lessen customer chemical inhalation exposures (City of Santa Rosa, 2017b; PID, 2018b; SLVWD, 2020), but the magnitude of reductions were not quantitatively reported. Water systems with similar damage and equal contamination sometimes issued different or no formal advisories in the same state (Odimayomi et al., 2021). When you compare the content of post-fire advisories, some populations were permitted to take "lukewarm" showers to reduce exposure, but others were not warned about shower temperature. One notification recommended bathing with the contaminated water, while the other notifications did not. Interestingly, the Centers for Disease Control and Prevention (CDC) does not recognize a "Do Not Drink-Do Not Boil" Advisory with current guidance (USCDC, 2022) or their toolbox (USCDC, 2016). While a 2021 drinking water contamination incident in Hawaii highlighted that explicit water system notification is legally required for short-term chemical exposure risks (USEPA, 2022), neither states nor the USEPA have acted similarly on this requirement for wildfire-impacted water systems. Further, current contaminated water use recommendations are not linked to chemical health risk assessments. Clarification on post-wildfire *Public Notification* from the USEPA should include explicit contents in the post-fire advisories and conditions that prompt their issuance and removal.

4.6 | A risk tradeoff analysis is needed for flushing wildfire-contaminated drinking water

To rapidly restore pressure and bacteriological control of water distribution systems under emergency conditions, removing the contaminated water as fast as possible is a critical objective. This was a major objective during the Marshall Fire response as the loss of pressure jeopardized the fire-fighting capability and the use of buildings. Also influencing that urgency was the focus to remove potential chemical contamination to limit the chance of customer exposure, and to avoid irreparable damage to plastics permeated by the chemicals. Under emergency conditions, typical routine flushing actions (i.e., thorough chemical characterization, dechlorination) may not be reasonable or applicable and require tradeoffs. When stagnation time becomes protracted with highly contaminated drinking water, the complexity of infrastructure damage can be compounded and delay the return to service (i.e., VOCs and SVOCs can penetrate into plastics).

There is a disconnect between current government policy and utility experiences that should be addressed. After distribution system contamination events, USEPA, Office of Water (2012a, 2012b) recommends several decontamination actions (i.e., chemical testing, capture, and obtaining state-issued permits before discharge), but the water utility sector has expressed operational feasibility concerns (WSCC, 2018). When the USEPA recommendations were followed after a water distribution system petroleum contamination incident in 2021, the speed at which the contamination was removed was impeded. The water system was ordered by the state to hold the VOC and SVOC-contaminated water in their network (and also building plumbing), and this stagnation lasted for about two weeks before discharge (Teruya, 2021). Permission to proceed with hydrant flushing required the acquisition and deployment of 21 activated carbon treatment units (Harlow, 2021). These assets were flown from the U.S. mainland to Hawaii using military resources. It is unclear how a similar response action can be replicated at a utility that does not have U.S. military resources. Similar water distribution system contamination events have occurred nationwide (Casteloes et al., 2015; Whelton, Dietrich, & Gallagher, 2017; Whelton, McMillan, et al., 2017). The USEPA should perform a feasibility assessment of their water distribution system contamination flushing policy as it pertains to wildfires, chemical spills, and other incidents.

5 | CONCLUSION

This case study documented the initial response and recovery actions of six public water systems following the 2021 Marshall Fire in Colorado. Key events during the first 24 h of the response primarily pertained to maintaining water pressure and basic operations. The unavailability of electric and natural gas to the water systems coupled with structure destruction and leaks prompted water pressure challenges. Water pressure was essential to support fire-fighting activities, as well as minimize contamination from entering the water distribution systems. Because of an imminent water pressure loss that would hinder fire-fighting operations, one utility bypassed its WTP and sent untreated lake water into its distribution system. The loss of communication with water distribution system tanks and other components prompted utility staff to enter the fire zone to assess system integrity and stop water loss. To minimize water loss, utility staff physically shut off damaged properties and subdivisions from the water distribution system by closing valves, curb stops, and removing water meters. Where a meter was not removed, a property owner turned the water service back on without utility consent and created an unauthorized cross-connection. Mutual aid from neighboring water systems and external scientific experts helped system owners and operators stabilize their damaged systems, find and remove contamination, and restore services.

Understanding which drinking water contaminants are present and their magnitudes are necessary to assess the health risk posed to water users, but several chemical water sampling and analysis issues were found. First, public water systems were not aware of the unique practices needed for post-fire VOC and SVOC water sampling. This included what specific chemicals to test for, how to collect post-fire samples, and how to interpret the results. Many commercial laboratories contacted for assistance could not provide sampling support hindering the speed to assess water safety. No laboratories could meet the 24 h turnaround time needed to expedite the water distribution network restoration process. SVOCs were detected in one damaged distribution system weeks after the fire, but the full range that they were initially present in the damaged system or in other water distribution systems remains unclear. The detection of off-tastes and off-odors in Superior's source water and distribution system revealed that their drinking water source was contaminated with SVOCs.

Several scientific and policy actions could help improve water utility and state-level wildfire response and recovery. First, workers should be equipped with PPE and trained for occupational hazards they could encounter during a wildfire. Second, utilities should conduct emergency response exercises to gain practice working through potential scenarios. The impact of wildfires on infrastructure, depressurization, and therefore the entry of chemical contamination into the distribution system, can be minimized by maintaining water pressure. Topping off all finished water storage as the wildfire approaches, having backup emergency power, and neighboring utility interconnections can lessen the chance depressurization occurs. Additional distribution system upgrades (backflow prevention devices on service lines, use of auto-shutoff meters/valves, keeping plastic infrastructure away from heat sources, etc.) can also reduce the potential for damage, depressurization, and contamination. To prevent water distribution system contamination by damaged or destroyed properties, water meters should be removed. At the federal level, the type and contents of public notifications as well as conditions prompting their issuance and lifting should be defined. Requirements for flushing contaminated water from the distribution network should also be addressed. Research is needed to better identify the conditions that prompt VOC and SVOC contamination of distribution systems and which compounds should be tested for post-fire. Post-fire water sampling, analysis, and system restoration methods should be further standardized, and wildfire response and recovery lessons learned should be shared across the sector.

AUTHOR CONTRIBUTIONS

Andrew J. Whelton: Conceptualization; resources; data curation; formal analysis; supervision; funding acquisition; validation; investigation; visualization; methodology; writing – original draft; project administration; writing – review and editing. **Chad Seidel:** Resources; data curation; formal analysis; funding acquisition; investigation; visualization; methodology; writing – review and editing. **Brad P. Wham:** Resources; data curation; formal analysis; funding acquisition; investigation; methodology; writing – review and editing. **Erica C. Fischer:** Formal analysis; funding acquisition; investigation; methodology; writing – review and editing. **Kristofer Isaacson:** Data curation; formal analysis; investigation; methodology; writing – review and editing. **Caroline Jankowski:** Data curation; formal analysis; investigation; methodology; writing – review and editing. **Nathan MacArthur:** Data curation; formal analysis; visualization; methodology; writing – review and editing. **Elizabeth McKenna:** Data curation; formal analysis; visualization; methodology; writing – review and editing. **Christian Ley:** Data curation; formal analysis; methodology; writing – review and editing.

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CONFLICT OF INTEREST

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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

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