Wildfire caused widespread drinking water distribution network contamination

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Abstract
The Tubbs Fire (2017) and Camp Fire (2018) are the first known wildfires where widespread drinking water chemical contamination was discovered in the water distribution network and not in the source water after the fire. In both disasters, drinking water exceeded state and federal government-defined exposure limits for several volatile organic compound (VOC) contaminants (e.g., benzene at 40,000 μg/L [Tubbs] and >2,217 μg/L [Camp]). This work outlines factors that influence wildfire-induced drinking water quality threats based on the findings from these two fires and explores related scientific and policy issues. For example, certain plastics in the network may serve as a primary VOC source through in situ plastic pyrolysis. Depressurization of the distribution network likely transported contaminated water that subsequently contaminated undamaged infrastructure. As wildfires at the wildland–urban interface are likely to occur more frequently, greater scientific evidence is needed to guide agency responses that will better protect public health.

KEYWORDS
disaster, plastics, water distribution network, water quality, wildfire

1 INTRODUCTION

The deadliest and most destructive wildfires have occurred in the wildland–urban interface, the crossroads of human-driven development and largely untouched wildlands, where dry wildland fuel brings fire directly to densely populated areas. The fatalities and destruction associated with the 2017 Tubbs Fire in Sonoma and Napa Counties in California and the 2018 Camp Fire in Butte County, California, underscore the risks faced in wildland–urban interfaces. In California alone, more than 2.7 million people live in very high fire hazard severity zones (Sabalow, Reese, & Kasler, 2019), and wildfire risk increases with changing climate (Westerling & Bryant, 2008).

It is well known that wildfires can contaminate natural waters, including drinking water sources, with ash...
pollution and sediment (Emelko, Silins, Bladon, & Stone, 2011; Smith, Sheridan, Lane, Nyman, & Haydon, 2011). Contamination often can be addressed by optimizing treatment before water enters the buried water distribution network. In contrast, the Tubbs and Camp Fires are associated with hazardous chemical contamination isolated in the buried distribution networks. Benzene and other volatile organic compounds (VOCs) were found to be above state and federal drinking water exposure limits (Table 1; U.S. Environmental Protection Agency [USEPA], 2018; USEPA, 2018; SWRCB, 2018a, 2019d).

This disaster, with drinking water contamination triggered by wildfire, falls into an interesting emerging hazard category of “Natech” (natural disasters triggering technological disasters; Cutter, 2018). Natech disasters often involve hazardous material release from pipelines and underground storage tanks damaged by a natural disaster (Krausmann, Renni, Campedel, & Cozzani, 2011)—e.g., Hurricane Katrina (Picou, 2009) or the Wenchuan earthquake (Krausmann, Cruz, & Affeltranger, 2010). Uncertainty and contested data interpretation present additional post-disaster social and information challenges (Gill & Ritchie, 2018); thus, a careful examination of data is needed.

In this work, the authors outline factors that influence wildfire-induced drinking water quality threats based on the experience of these two fires. The authors also explore related scientific and policy issues. While only two cases of post-wildfire widespread chemical contamination have been found, study results are likely applicable to wildland–urban interfaces exposed to similar risks around the world. Results presented can be used to prioritize research and develop evidence-based response and recovery guidelines for future contamination events.

2 | APPROACH

In January 2019, the authors were asked by the Paradise Irrigation District (PID) to provide technical assistance regarding water contamination response and recovery caused by the Camp Fire. In February 2019 and March 2019, some of the authors visited the disaster area to provide response recommendations (PID, 2019) and explain scientific challenges. Starting in January 2019, some of the authors participated in the twice-weekly California Governor’s Office of Emergency Services (CalOES) Camp Fire Water Task Force meeting. Some authors also generated scientific opinion memorandums in collaboration with USEPA and submitted them to the task force (Whelton, Lee, & Proctor, 2019). In June 2019, some of the authors visited Paradise to host independent public information events.

This study involved the analysis of chemical water-testing records, review of response and recovery documents, and discussions with various responding agencies for the Tubbs Fire and Camp Fire. The organizations contacted included the City of Santa Rosa, California; Town of Paradise, California; CalOES; California State Water Resources Control Board (SWRCB); PID; Del Oro Water Company (DOWC); Butte County Health Department (BCHD); USEPA-Region 9; USEPA Office of Research and Development-Cincinnati; and U.S. Federal Emergency Management Agency (FEMA)-Region 9. The City of Santa Rosa provided the information regarding the Tubbs fire, including the master file of chemical water-testing results, standard operating procedures (SOPs) used by the city, information regarding source investigations, and the city’s recovery plan. Camp Fire chemical water-testing records were obtained by accessing the public online databases on the PID and DOWC websites (downloaded July 24, 2019), as well as directly from the SWRCB, PID, and DOWC. Records included analysis for VOC, semivolatile organic compounds (SVOCs), tentatively identified compounds, and ad hoc drinking water visual and odor descriptions recorded by water samplers. Documents were also obtained from utility and state agencies (e.g., water system recovery plans and health risk assessments).

3 | RESULTS AND DISCUSSION

3.1 | The Tubbs Fire in Santa Rosa, California

On October 8, 2017 (Tables 1 and S1), the Tubbs Fire started in Sonoma County and burned 36,807 acres. Of the 5,656 structures destroyed (CalFire, 2018), approximately 3,100 were in Santa Rosa (Black & Veatch, 2018). Since distribution network depressurization occurred, a boil water advisory (BWA) was issued on October 10, 2017, to the Fountaingrove and Oakmont service areas, affecting approximately 3,800 addresses (USEPA, n.d.; Sonoma County Sheriff’s Office, 2017). A month after the fire, a customer complained about the off-odor of drinking water. Within two days, the city sampled 13 hydrants and found maximum benzene and toluene concentrations of 6.9 μg/L and 2.4 μg/L, respectively. Since benzene exceeded the federal maximum contaminant level (MCL) of 5 μg/L and the California MCL of 1 μg/L, the city issued a Do Not Drink–Do Not Boil (DNB–DNB) advisory to a specific area of Fountaingrove containing 13 standing homes (November 10, 2017) (City of Santa Rosa, 2017, 2018; Santa Rosa Water, 2018). This area included 5.2 mi (0.08%) of the city’s 619 mi of the water...
### Table 1  Key water system contamination response and recovery events following the Tubbs Fire and Camp Fire

| Date (days since fire) | Event/notice/advisory                                                                                     |
|------------------------|-----------------------------------------------------------------------------------------------------------|
| October 8, 2017 (0)    | Fire started.                                                                                             |
| October 10, 2017 (2)   | Boil water advisory (BWA) issued by the City of Santa Rosa Water to Fountaingrove area.                    |
| Late October (10–20)   | Evacuations lifted (varied by specific neighborhood).                                                      |
| November 8, 2017 (31)  | Odor complaint by a customer in the area. City sampled one nearby hydrant and found benzene (max. 4.9 μg/L) and toluene (max. 1.6 μg/L). |
| November 10, 2017 (33) | BWA changed to Do Not Drink water advisory. The Do Not Drink and Do Not Boil advisories were issued for two specific areas of Fountaingrove, affecting 13 standing homes. |
| October 11, 2018 (368) | Water advisory lifted.                                                                                     |

**Tubbs Fire events (limited to advisory events within eight months of when the fire started)**

| Date (days since fire) | Orga | Event/notice/advisory                                                                                     | Area          |
|------------------------|------|-----------------------------------------------------------------------------------------------------------|---------------|
| November 8, 2018 (0)   |      | Fire started.                                                                                             |               |
| November 9, 2018 (1)   | PID  | BWA issued.                                                                                               | PID           |
| November 11, 2018 (3)  | DOWC | BWA issued for five DOWC systems (including three affected systems).                                        | DOWC          |
| November 21, 2018 (13) | DOWC | BWA lifted for all DOWC systems (some earlier).                                                            | DOWC          |
| Early December (20–30) |      | Evacuations lifted (orders varied by specific neighborhood).                                               |               |
| December 20, 2018 (42) | PID  | BWA changed to Do Not Drink water advisory—no drinking or boiling, limit water use (i.e., lukewarm, not hot showers). | PID           |
| December 24, 2018 (46) | SWRCB| Conditional water advisory—if there are odors, you should not use water and should contact the utility.    | PID and DOWC  |
| January 9, 2019 (62)   | DOWC | Press release—no limit on drinking, investigating issues, conditional advisory with odors.                  | DOWC          |
| January 11, 2019 (64)  | SWRCB| Notice—benzene found in both PID and DOWC, but have different water advisories (PID's Do Not Drink versus DOWC's conditional). | PID and DOWC  |
| March 5, 2019 (117)    | SWRCB| Updated advisory—odor no longer enough to indicate a problem. No limits on water use.                        | DOWC          |
| March 19, 2019 (131)   | BCHD | Public advisory on water—water unsafe to drink, do not rely on home treatment devices for contaminant removal. | Butte County  |
| June 14, 2019 (218)    | SWRCB| "Information to Water Customers Regarding Water Quality in Buildings Located in Areas Damaged by Wildfire“ released with advice on flushing and testing. | All           |
| July 15, 2019 (249)    | PID  | At 94 specific buildings, water advisory lifted based on testing.                                          | PID           |
| August 6, 2019 (271)   | BCHD | Advisory on water lifted/modified—rely on utilities‘ information, test your building according to SWRCB June guidance if wanted. | Butte County  |
| August 9, 2019 (274)   | SWRCB| "Information to Water Customers” updated with added treatment options and revised information on flushing.    | All           |

*Note: For dates on when samples were collected, citations, and further details see Table S1. Sources, notices, and a more detailed timeline can be found in supplementary information (Table S1). DOWC, typically refers to the three affected systems named Paradise Pines, Magalia, and Lime Saddle.*

*aOrganization (org) abbreviations are as follows: BCHD, Butte County Health Department; DOWC, Del Oro Water Company; PID, Paradise Irrigation District; SWRCB, State Water Resources Control Board.*
distribution network. The city supplied drinking water to 175,155 people, but only about 10 people were directly affected by the DND–DNB water advisory. On October 11, 2018, the DND–DNB advisory was lifted.

Within the advisory area, all service lines were replaced. To identify water distribution network components that were still contaminated, a SOP was adopted approximately in January 2018. This procedure included (1) a preflush, (2) 72-hour stagnation, (3) water sampling, and (4) chemical analysis (SI 1). Of the 3,301 locations tested, 456 locations were inside the advisory area. In month 6 of the response, service line testing was expanded to cover everything within 500 ft of a burned parcel, in addition to within the advisory area. For these samples, 72-hour stagnation was not always established (i.e., some samples were collected at homes actively using water).

Most of the locations tested were service lines, with a total of 3,103 service line locations tested (351 inside the advisory area). Benzene concentrations exceeded 0.5 μg/L at 351 service line locations (174 inside the advisory area, even after initial service line replacement). The city replaced service lines when benzene was present at ≥0.5 μg/L after repeated sampling, a criterion lower than the California MCL. Water meters were replaced at approximately 2,875 locations because of high benzene concentrations or other fire damage.

The response was expedited by heavy use of the city-owned certified drinking water laboratory, alongside use of external testing laboratories. As of May 2019, approximately 8,400 water samples had been analyzed to address and monitor the situation. Some locations were sampled repeatedly (one hydrant 57 times), and split samples (at least 134 splits) were analyzed for quality control (QC). In some cases, sites deemed free of benzene were later found to have water in violation of benzene MCLs (Figure S1). Split samples produced a maximum 77% difference in benzene concentration when benzene values were between 0.5 and 1.0 μg/L and a 11% difference when benzene values were >1.0 μg/L. Water samples were screened for a total of 101 VOCs over the response, but the number and specific analytes varied over time and by lab (Figure S2 and Table S2). The city continues to implement a long-term VOC water quality monitoring plan throughout the system.

The initial estimated cost to remove and replace the affected water distribution network components was US $44 million. However, by sampling at each asset and flushing the affected water distribution network, the city was able to avoid complete system replacement. The total response and recovery costs were reduced to about $8 million, and much of these costs were reimbursed by state and federal emergency funds.

3.2 The Camp Fire, Butte County, California

The Camp Fire in Butte County started on Camp Road on November 8, 2018 (Tables 1 and S1). The fire burned 153,336 acres and has been referred to as the most destructive and deadliest in California’s history, with 86 fatalities (CalFire, 2019). An estimated 18,804 structures were destroyed (CalFire, 2019), of which about 9,000 constituted 95% of the Town of Paradise. An estimated 1,400 standing structures remained in the PID service area (Figure S3). More than 40,000 people were issued BWAs (Table S3). The two large water systems affected were PID and DOWC (Figure S3), which issued BWAs on November 9, 2018 (PID, 2018a), and November 11, 2018 (DOWC, 2018), respectively. DOWC lifted its BWAs by November 21, 2018.

A total of 3.5 weeks after lifting its BWAs, DOWC collected water samples from hydrants and customer hose bibbs in its service area. Results received approximately 2 weeks later revealed that benzene (max. 8.1 μg/L, n = 8) exceeded federal and California MCLs (DOWC, 2019). DOWC did not issue a water advisory after this discovery. However, PID changed its BWA to a DND–DNB water advisory (PID, 2018b) (December 20, 2018), even without its own water testing data. This DND–DNB water advisory affected 10,500 service connections and a prefire service population of 26,032 people (Table S3).

From months 2 to 8, multiple organizations issued and changed their conflicting water use advice. In December 2018, SWRCB issued a statement that odors may indicate unsafe water (SWRCB, 2018c). In early January 2019, DOWC issued a statement that there were no water use restrictions for their systems unless odor was detected. This advice was given despite the fact that a VOC odor thresholds are often higher than MCLs and at concentrations that cause acute health effects (Table S4). In mid-January 2019, SWRCB stated that it approved the different advisories, wherein PID customers were advised to use only bottled water, and DOWC customers should feel “safe drinking their water unless they detect odors reminiscent of plastic or fuel” (SWRCB, 2019e). In March, BCHD issued its own advisory that “residents should not use tap water for drinking, cooking, food preparation, brushing teeth or similar activities” (BCHD, 2019a), similar to PID’s DND-DNB advisory. This statement affected all Butte County residents, including PID, DOWC customers, and private well owners. Months later, SWRCB changed its position and said odor was no longer a sufficient indicator of contamination (Table 1) (SWRCB, 2019g).

Eight months after the fire, official advisories largely remained unchanged. In summer 2019, PID began lifting
the DND–DNB advisory for individual properties as they repressurized their system, removed contaminated assets, and tested each customer meter. In August 2019, BCHD revised its advisory and recommended citizens contact their utility/ follow that advice (BCHD, York, & Miller, 2019). DOWC never issued a DND–DNB advisory, even though VOC federal and California MCLs were exceeded in its distribution networks.

An estimated 2,438 private drinking water wells were also affected by the Camp Fire (California Department of Water Resources, 2019). While initial testing guidance included only standard contaminants (e.g., bacteria), well owners were advised to check for VOCs (Table S1) since their plumbing, both in buildings and buried outside, was similarly vulnerable to VOC contamination. Six months after the fire, heavy metal and polycyclic aromatic hydrocarbon contamination was found in creeks and rivers, and BCHD issued additional testing clarifications to include these contaminants and standard stagnation (BCHD, 2019b).

3.3 Comparison of approaches and results

3.3.1 Sampling approach

During the first 8 months of response, PID collected 1,699 water samples in its distribution network (Figure 1), including 772 service line samples (282 for standing structures, 487 for burned structures, 3 unmarked), 624 samples representing the water mains, and 303 samples from other assets. An additional 98 blanks were tested for quality control. For DOWC’s systems, 200 valid samples had been reported (with an additional 22 with data points omitted because of long sample-holding times and 8 omitted for other reasons: for example, no standing home nearby, no reason given). At least one additional sample was collected by SWRCB in PID (not included in Figure 1). In comparison, Santa Rosa had collected 5,244 samples in 8 months (Figure 1).

The SOP varied widely between events and jurisdictions, especially regarding stagnation. Within the advisory area in the Tubbs Fire, an SOP with 72-hour stagnation was established (SI 1) but was not consistently applied outside the advisory area. For the Camp Fire, PID took most of its samples with 72-hour stagnation. In DOWC, many samples from actively used service lines were taken “on the fly,” with no measured stagnation (Cooper, 2019), and others were taken with a 48-hour stagnation period.

3.3.2 Analysis approach

Although benzene has received the most attention in these events, VOCs other than benzene exceeded their exposure limits in both events (Table 2), and some VOC exceedances occurred when benzene was not present. Since most samples collected in the first 2.5 months after

![Figure 1: Number (top) and proportion (bottom) of samples taken during the first 8 months after Tubbs Fire (left) and Camp Fire (right). Color indicates the benzene level of each sample, divided into nondetects, below 0.5 μg/L, below 1.0 μg/L (and above 0.5), below 1.5 μg/L (and above 1.0), and above 1.5 μg/L. On the top, n is the total number of samples taken in each month. On the bottom, the number of samples falling into each category is marked. This analysis excludes blanks and samples disqualified for long holding times but does include duplicates and samples representing a variety of locations, including water mains, service lines, reservoirs, and sample stations. Further details on data treatment are included in SI 6.](image-url)
the Camp Fire were analyzed for benzene only, the true extent of contamination was likely not captured. In early February (approximately 3 months post-fire), the SWRCB found a single water sample in PID’s area containing benzene (>2,217 μg/L), naphthalene (693 μg/L), toluene (676 μg/L), styrene (378 μg/L) (Table 2), ethyl benzene (76 μg/L), xylenes (66 μg/L), other confirmed VOCs, and several tentatively identified compounds (SI 2). In Santa Rosa, SVOCs and tentatively identified compounds were also found in damaged infrastructure leaching tests (SI 3). Heavy metals, polycyclic aromatic hydrocarbons, and SVOCs were also found in Camp Fire samples (SI 4).

Several measures were suggested for use as indicators that contamination occurred, including odor and benzene-only analysis (SWRCB, 2019a, 2019e). Odor was sporadically described in Camp Fire data, but no clear relationships could be found with VOC presence. In March, SWRCB concluded that, while odor was not an effective indicator of contamination, benzene was (SWRCB, 2019g). In Santa Rosa, the concentration of several VOCs exceeded regulatory exposure limits when benzene was not present (Tables S2 and S5). For example, when benzene was not detected, dichloromethane was found at 41 μg/L (5 μg/L federal MCL), and tert-butyl alcohol was found at 22 μg/L (12 μg/L California notification level) (Table S5). Eight months after the Camp Fire, numerous VOCs had been found in the PID water distribution network samples (Table S6). DOWC had tested for multiple VOCs at 31 locations (DOWC, 2019).

### 3.3.3 Trends in benzene concentrations

For the first 8 months after both fires, benzene levels did not exhibit a strong temporal trend (Figure 1). This is not entirely surprising since sampling targets, SOPs, and scope also changed over time. While values might be expected to be the highest immediately following the fire and to reduce over time, contamination was also geographically sporadic and likely moved around the system, further complicating predictability. Even in specific locations, temporal trends were not as expected (Figure S1). Benzene contamination persisted in Santa Rosa until month 11 following the fire (Figure S4). It is unclear when PID and DOWC, and the affected properties, will be free of contamination.

In both events, samples were taken both with and without flushing, with samples taken after flushing...
representing the water mains. Typically, flushed samples had lower levels of contamination than initial samples, representing asset-specific contamination. Of samples marked “flushed” in Santa Rosa (n = 323 in the first 8 months), the maximum concentration of benzene was 0.57 μg/L. In PID, water main samples had a nondetect rate of 97% for benzene, with a minimum reporting level of 0.5 μg/L, while service line samples had 75% non-detects. However, in PID’s system, 14 samples representing water mains exceeded 1.0 μg/L benzene, with a maximum of 22 μg/L and a value of 10 μg/L detected as late as June 2019, which may indicate continued contaminant movement in the system.

### 3.3.4 | Hydraulic challenges

The hydraulic effects of the Tubbs Fire were limited (Black & Veatch, 2018) compared with the effects of the Camp Fire. In the City of Santa Rosa, utility staff shut off service lines and valves within several days. Partly because of this controlled hydraulic effect, the water advisory area was geographically limited. High VOC levels were found outside this advisory area, including all maximum concentrations of regulated compounds (Table S5). It is unclear from the data whether these levels affected occupied homes. The greater hydraulic impacts of the Camp Fire were in part because of the fire’s speed (33 km/hour) (Chambers, Gorman, Feng, Torn, & Stapp, 2019). PID was unable to shut off service lines and valves before evacuation, and depressurizations occurred (estimated to affect 90% of the system). DOWC was able to isolate parts of its systems before evacuating.

To facilitate firefighting, utilities immediately addressed pipe failures by repressurizing the systems. While this was relatively quick in Santa Rosa and DOWC, PID had many physically damaged assets (e.g., a reservoir with cover damage), slowing efforts. Hydrants were leaking, thousands of meter boxes were destroyed, pipes were ruptured, and plastic residue seemed to have melted and cooled inside service lines (Figure 2). PID likely experienced very low and negative pressures. When field crews opened hydrants to flush contaminated water, they sometimes heard sucking noises, which indicated a continued vacuum inside the distribution network. Clouds of unknown material were also seen escaping the system months into repressurization efforts. Pipe breaks, in conjunction with negative pressure, might have also sucked in contaminated liquid or gas compounds into the water system (J. Lee, Lohani, Dietrich, & Loganathan, 2012). Thus, it is highly likely that contaminated water was moving inside PID’s system for some time following the wildfire.

## 4 | SCIENTIFIC AND REGULATORY CHALLENGES

### 4.1 | Determine sources, sinks, and transport mechanisms

The origin of VOCs in the post-wildfire water distribution networks requires further investigation. In Santa Rosa, investigations by the city, forensic chemists, and experts concluded that contamination (1) was not from underground storage tanks and (2) was related to the fire (City of Santa Rosa Water, 2018). The VOCs are hypothesized to be derived from in-situ plastic pyrolysis and/or water or air contaminants from structures burning and/or vegetation burning being drawn into the distribution network. A variety of plastic materials were present in all water distribution networks affected by the fires, including polyvinyl chloride (PVC), high-density polyethylene (HDPE), and polybutylene (PB) pipes, along with ethylene propylene diene monomer gaskets and polypropylene and nylon water meter components (Table S7). Thermal degradation of potable water system plastics has not been experimentally explored, but PVC thermal degradation can generate some of the VOCs found (Table 2), including benzene, toluene, naphthalene, and other aromatic compounds (Bockhorn, Hornung, & Hornung, 1999; Montaudo & Lattimer, 2002; Yu, Sun, Ma, Qiao, & Yao, 2016). Burning of a PVC storm sewer pipe revealed benzene and other aromatic compounds released into the air (Chong, Abduramoni, Patterson, & Brown, 2019). Water within pipes may have also reached high temperatures, and benzene has been recovered from both sub- and super-critical water in contact with PVC (Takeshita, Kato, Takahashi, Sato, & Nishi, 2004). Structure (Austin, Wang, Ecobichon, & Dussault, 2001a, 2001b) and vegetation fires can produce some VOCs found in the water (S. Lee et al., 2005).

Infrastructure may have become a sink or “secondary source” for contaminants: VOCs can diffuse into plastics and sorb to metal surfaces, biofilms, and sediment (Baltzis, Mpanias, & Bhattacharya, 2001; Huang et al., 2017; Selleck & Marinas, 1991). As VOCs subsequently leach out over time, clean water can become contaminated. Before the Camp Fire, USEPA reported that weeks to months could be needed to decontaminate VOC-contaminated small-diameter polyethylene water pipes at room temperature (Haupert & Magnuson, 2019). When responding to the Camp Fire, the authors and USEPA calculated that more than 1 year of continuous water flushing at 7.5 L/min could be necessary to return some 2.54-cm-diameter HDPE service lines to safe use (Whelton, Lee, et al., 2019). The flushing time needed is influenced by the degree of contamination, plastic type,
diameter, temperature, flow rate, and flow regime (e.g., Reynolds number), among other factors. For example, PVC pipes are more resistant to this type of contamination (Feng, Gaunt, & Kee Ong, 2009), and since known benzene concentrations were \( \leq 1,000 \text{ mg/L} \) (Ong et al., 2007) \( (10^6 \text{ μg/L}) \), PVC did not likely act as a secondary source. In Santa Rosa, a contractor exhumed HDPE pipes and found benzene leaching at 0.03 \( \text{μg/cm}^2 \), which would produce a theoretical concentration of 70 \( \text{μg/L} \) in a service line (SI 3).

Despite known pipe material interactions with VOCs, field data from Santa Rosa did not indicate a strong relationship between VOC contamination and material. Samples from metal service lines (ductile iron, steel, and copper) were somewhat less likely to demonstrate contamination of >1 μg/L benzene (11%, \( n = 1,573 \)) than plastic pipes (HDPE, PVC, PB, PE) (20%, \( n = 326 \)). However, the two locations with the highest measured benzene concentrations (40,000 and 2,400 μg/L) had copper service lines. Of the 21 service line locations with maximum benzene concentrations exceeding 100 μg/L, 8 were copper, 3 were a mix of HDPE and copper, and the remaining 10 were HDPE. The number of samples for each material type were highly unbalanced, and location and other factors likely confounded results, but it is still clear that material alone cannot be used as an indicator for likely contamination.
Building damage might also be considered a risk factor for contamination. In PID’s service area, service line water samples taken at destroyed structures had a higher level of benzene detection (34%, n = 487) than samples taken at standing homes and businesses (8.1%, n = 282). Similarly, the number of benzene MCL violations was higher for burned structures (25%) than for standing structures (4.2%). A similar trend was found in DOWC samples, with most reported detections (n = 33) found in occupied recreational vehicles (likely on burned lots), empty lots, and sampling stations. However, DOWC also had four additional detections at hydrants (unclear if flushed) and one detection of 8.1 μg/L benzene at a customer hose bibb (i.e., outdoor spigot; unclear how damaged structure was, found in the first month of response). In Santa Rosa’s data, the distinction between destroyed and standing structures was not made. There are several possible reasons for this trend. Standing homes likely had more flushing activities related to construction or occupation, removing contaminated water. Although PID used a 72-hour stagnation time, shorter stagnation times were often used in occupied homes in DOWC, which reduced the chance of detecting secondary source contamination. It is also possible that destroyed structures are the primary source of contamination. Still, service lines for standing homes were contaminated, so damage alone does not account for contamination.

While service line contamination is thought to affect only one building, this water can potentially affect water mains and other service lines through back-siphonage events during low- and negative-pressure events. In addition, hydraulic flow regimes can affect other contaminant transfer mechanisms. Better understanding contaminant transport will require more studies of VOC transport and calibrated post-fire hydraulic models. In PID’s service area, a checkerboard approach was adopted to prioritize infrastructure at standing homes. The advisory was lifted for a standing home (even if surrounded by destroyed structures that had contaminated service lines) if PID’s system was pressurized and testing results of the customer meter were free of VOCs above California MCLs. As of July 15, 2019, 94 PID utility service lines had their water advisories lifted in this way (PID & Kader, 2019). However, just as mains are vulnerable to recontamination from service lines, service lines are vulnerable to recontamination from mains after being declared clear.

4.2 | Control data quality

The initial Camp Fire response revealed analytical problems similar to the 2014 large-scale drinking water contamination incident in Charleston, West Virginia. There, the lack of SOPs and quality assurance/quality control resulted in erroneous data reporting (Whelton, McMillan, Novy, White, & Huang, 2017). During Camp Fire testing, spot-checking of commercial laboratories was not conducted, and duplicate samples, as required by USEPA Method 524.2 (USEPA, 1995), were not collected regularly. In April 2019, the SWRCB reported that its own analysis of a limited set of duplicate samples had up to ±290% variability in benzene concentrations (3.1 versus 12 μg/L) (Crenshaw, 2019a). This variability was higher than that observed in Santa Rosa.

The varied application of SOPs, both among and within jurisdictions, contributed to difficulty in trusting and interpreting data (Crenshaw, 2019b). Stagnation time can especially affect the likelihood of contaminant detection when either primary sources (pyrolyzed plastics, debris settled in the mains) or secondary sources (undamaged plastics acting as sinks for VOCs) are in contact with the water.

The presence of dichloromethane (methylene chloride) in water samples led to an interesting data quality issue that requires further investigation. The presence of dichloromethane was hypothesized to be laboratory contamination (SWRCB, 2019f), disinfection byproducts (Matheson & Tratnyek, 1994), remnants of a cleaning solution used in sampling (PID & Kader, 2019), and dehalogenation of trichloromethane by iron metal (Matheson & Tratnyek, 1994). However, PID reported at least 108 exceedances of the 5 μg/L federal MCL, that most drinking waters had levels below 1 μg/L (ASTDR, 2000), and that it was found in municipal buildings (Town of Paradise, 2019) (i.e., without the cleaning solution). Dichloromethane concentrations were also found in Santa Rosa to be as high as 41 μg/L and then 5.08 μg/L as late as 11 months after the fire.

4.3 | Develop water use restrictions to protect public health

BWAs must be reconsidered following fire events as they may increase acute VOC inhalation exposures. BWAs are a typical response to depressurization (USEPA, n.d.) but are primarily intended for microbiological contaminants (SWRCB, 2018b). For both the Tubbs Fire and Camp Fire, multiple VOCs, not just benzene, exceeded short-term drinking water exposure limits that could cause acute adverse health effects. These include naphthalene, tert-butanol, toluene, and vinyl chloride. While dichloromethane and styrene were only detected above long-term exposure limits, boiling can further increase VOC exposure: In March 2019, the California
Department of Public Health reported that boiling contaminated water from PID helped volatilize a number of VOCs, including benzene, benzo[a]furan, chloroform, ethyl benzene, indene, naphthalene, and toluene (Draper & CDPH, 2019). The same study, where study participants were exposed to the contaminated water, resulted in the reporting of adverse health effects such as throat irritation, even when odor could not be detected (Draper & CDPH, 2019).

Recommendations permitting contaminated water use for other applications may have also been inadequate. In April 2019, the California Office of Environmental Health Hazard Assessment (OEHHA) reported that drinking water exposures to benzene as low as 26 µg/L may cause acute adverse health effects (i.e., effects after a short exposure; OEHHA, 2019). SWRCB subsequently estimated that PID’s water use restrictions provided a “60% margin of safety” for chemical exposure (Miguelino, 2019). While PID issued a recommendation for residents to only use “lukewarm water” for showering, discussions revealed that the advisory was based only on an untested assumption: lowering showering temperatures would reduce exposure because volatilization rates are higher at high temperatures. Models developed after the 2014 chemical spill in West Virginia demonstrated an ability to estimate chemical exposures (Omur-Ozbek, Akalp, & Whelton, 2016; Sain, Dietrich, Smiley, & Gallagher, 2015), but were not used following these fires. Both existing and newly developed air contamination models should be integrated into response and recovery decisions.

4.4 | Policy decisions

As decisions are difficult to make during disaster response, policy should clarify priorities before the next disaster. For example, the decision to replace infrastructure was weighed against flushing. Santa Rosa flushed its system to decontaminate, but after 3 months of flushing, some benzene levels had not been reduced below the California MCL. Thus, the city began replacing hydrants, water mains, service lines, and meters. During the Camp Fire response, some flushing was conducted, but excessively long continuous flushing times were estimated to be necessary, more than 280 days in some cases (Whelton, Lee, et al., 2019). Flushing may also create hazardous waste: during PID’s Camp Fire response, the issue of disposing chemically contaminated waste was raised since benzene exceeding 500 µg/L may constitute hazardous waste (discussed further in SI 5). Strategies to predict and validate decontamination success, and thus the value of flushing efforts, are needed.

It remains unclear what type of testing is required to achieve certainty about drinking water and infrastructure safety, as well as what thresholds should be used for infrastructure replacement and being declared “clear.” During the Camp Fire response, it was proposed that only “benzene at >1 ppb” posed a health risk (SWRCB, 2019a), despite the risks of benzene-only testing described earlier (i.e., presence of other fire-associated VOCs in the water). There is high variability in replicate water samples in these events and at low concentrations (described earlier). Thus, a lower threshold (i.e., 0.5 µg/L benzene) would be more conservative and provide a necessary factor of safety. Interpretation of measured values is also problematic, since a measured value of 1.4 µg/L could be rounded down to 1 µg/L and thus be considered in compliance (Crenshaw, 2019c). Moreover, practices applied from a SOP can affect observed results. Policy can better define what will be considered in compliance and an acceptable health risk to those exposed to contaminated water before the next disaster.

During the Camp Fire response, decisions were delayed by the lag time between collecting a water sample and obtaining the results. Commercial laboratories took 5–14 days to provide results. Unlike Santa Rosa, the utilities affected by the Camp Fire did not have onsite analytical testing capabilities. While development of onsite capabilities or mobile laboratory deployments was discussed, these were rejected by the SWRCB. The importance of speed in response should be clearly conveyed, and the development of faster contaminant (e.g., VOC, SVOC) detection methods should be prioritized.

Many recovery decisions were influenced by financial concerns. In both fires, recovery was estimated to be very expensive (PID & Kader, 2019), and utilities faced significant financial challenges. PID alone estimated that total recovery could cost between $23.4 million and $32.5 million and take 2.5 to 5 years to complete (PID & Kader, 2019). Although water contamination was related to wildfire, which has many costs covered by state and federal emergency funds (e.g., FEMA), the reimbursement process was not straightforward (PID, 2019). For FEMA reimbursement to be considered, every asset had to be tested before replacement at the time this study was completed. Protecting public health is paramount, and better understanding of these incidents can also facilitate valuable cost–benefit analyses and more cost- and time-effective policies.

4.5 | Private property challenges

Individual building owners are responsible for their own plumbing (i.e., service line and indoor plumbing
network), but plumbing was delivered contaminated water and not studied immediately after either fire. Studies are needed to examine chemical–material interactions and develop evidence-based testing and decontamination procedures. Plumbing systems likely contain plastics (e.g., pipes, water heater dip tube, gaskets, shower hoses), which could become secondary contamination sources. Plumbing decontamination can be arduous, even with contaminants that do not sorb to pipes, sediments, or biofilms (Casteloes, Brazeau, & Whelton, 2015; Hawes et al., 2017). Once plumbing is free of the contaminants, it may be vulnerable to recontamination during hydraulic events (discussed earlier).

Plumbing safety guidance was inadequate. None was given in the Tubbs Fire response, and the water advisory did not affect many people (Santa Rosa Water, 2018). After the Camp Fire, thousands of people received non-potable water for many months. Seven months after the fire, SWRCB issued guidance for standing structures, advising to test for benzene only contamination of kitchen sink cold water (SWRCB, 2019c). It was deficient for a number of reasons, including inadequate stagnation time, sole focus on benzene, and consideration of only one exposure location (excluding hot water plumbing and service lines) (Whelton, Rhoads, et al., 2019). Early guidance by BCHD “not [to] rely on home water filtration systems as they may not be adequate to provide needed protection” (BCHD, 2019a) was later countered when, 9 months after the fire, SWRCB issued its own guidance document, which added that “granular activated carbon (GAC) will effectively remove benzene and other organic contaminants from water” (SWRCB, 2019b). No information was given on the size or capacity of systems necessary to remove Camp Fire contamination. In particular, some survivors relied on small carbon filters built into their refrigerators to treat the contaminated water, while others installed whole house activated carbon filtration systems and also added undersink filtration systems at select facets.

5 | CONCLUSIONS

Basic scientific research and improvements to disaster governance designs are required to improve drinking water safety and community resilience. Although our comparative analysis provides some useful insights, the exact causes of water contamination in these two cases are still unknown because of insufficient data. Policy improvements should be prioritized for communities located in wildland–urban interfaces. Several minor policy changes could improve public health protection. In the longer term, building codes might mandate backflow prevention at all service lines, easily accessible corporation stop shutoff valves, and prohibition of materials that can be primary sources of contamination (releasing chemicals with pyrolysis) or secondary sources (adsorbing chemicals).

To address these issues, the authors recommend the following:

- In future events, rapid, standardized, and widespread testing will assist in determining the sources, vulnerable assets, and transport mechanisms of contamination.
- Validated SOPs and use of controls are needed to establish trust in results.
- After a wildfire in the wildland–urban interface, a strict “Do Not Use” water order should be issued to protect public health.
- Policy priorities should be defined before the next disaster to facilitate utility and public health response.
- Guidance to homeowners needs significant improvement to protect public health and plumbing infrastructure.

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CONFLICT OF INTEREST

The authors do not declare any conflicts of interest.

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**SUPPORTING INFORMATION**

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

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