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Decontaminating chemically contaminated residential premise plumbing systems by flushing†

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Recent large-scale drinking water chemical contamination incidents in Canada and the U.S. have affected more than 1 000 000 people and involved disparate premise plumbing decontamination approaches. In this study, past premise plumbing decontamination approaches were reviewed and a mass balance water heater model was developed and tested. Organic contaminants were the sole focus of this work. Thirty-nine contamination incidents were identified and contaminants had a wide range of physiochemical properties [*i.e.*, $\log K_{ow}$, water solubility, vapor pressure]. Minimal data was available pertaining to flushing protocol design and effectiveness. Results showed that premise plumbing design, operational conditions, contaminants present and their properties, as well as building inhabitant safety have not been fully considered in flushing protocol design. Results indicated that flushing could decontaminate some, but not all plumbing systems. Several modeling scenarios showed contaminant levels exceeded drinking water health limits after flushing following recent large-scale water contamination incidents. Water saving fixtures and devices, water heater size, and flow rate affected contaminant removal efficiency. Modeling did not consider service lines or piping. This study provides a first step in the development of science based premise plumbing flushing protocols for organic contaminants.

Water impact

Premise plumbing systems provide building inhabitants access to safe drinking water. When plumbing is accidentally or intentionally chemically contaminated, the stored drinking water and plumbing components can be rendered unsafe. This study reviewed the effectiveness of premise plumbing decontamination protocols. A rationale was proposed for designing flushing protocols that consider system design, operation, organic contaminant properties, and building inhabitant safety.

Introduction

In Canada and the U.S., several large- and small-scale drinking water chemical contamination incidents occurred between early 2014 and mid 2015. Combined, these incidents affected more than 1 00 000 people. Upwards of 150 000 premise plumbing systems were contaminated by a variety of organic contaminants. Premise plumbing components include the service line and piping within the building as well as various appurtenances (*i.e.*, tanks, valves, fixtures). Buildings impacted by these events were residences, schools, hospitals, government buildings, and businesses. In all of these incidents, premise plumbing flushing was recommended to remove contaminated water and enable building inhabitants to regain safe drinking water access. However, a series of recent discoveries has prompted a need to more closely examine premise plumbing decontamination procedures.

In January 2014, coal washing pollutants contaminated the water supply for 300 000 residents in West Virginia, USA, affecting 15% of the state's population. Due to the water's unknown toxicity, officials warned customers not to use the water except for toilet flushing and firefighting activities.[1] Over the next four to nine days while the water distribution system was flushed, the utility directed the community to flush the licorice smelling water from their premise plumbing by running hot water taps for 15 minutes, cold water taps for 5 minutes, and appliances for 5 minutes.[2] The State of West Virginia also issued a different set of flushing procedures specifically for premise plumbing systems that discharged to septic tanks.[3] Both protocols recommended flushing contaminated hot water first, and neither were pilot tested. Follow-up investigations revealed that some coal

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washing pollutants diffused into plastic plumbing pipes and flushing did not always reduce contaminant levels at resident taps; in some cases contaminant levels were higher after premise plumbing flushing.[1,4] Additionally, some contaminants volatilized into buildings during flushing and this exposure contributed to population illness.[1] While the utility, local health departments, and state agencies did not issue safety precautions to the public, the American Federation of Teachers and State of West Virginia warned school staff to avoid vapor exposure and wear personal protective equipment (PPE).[5,6]

In December 2014 and January 2015, petroleum odors were detected in Washington, D.C. and Glendive, Montana drinking water. The public was initially directed to limit water contact as responders investigated the incident causes and extent of water utility distribution system contamination. After flushing the water distribution system in Washington, D.C., the utility recommended that the public flush their premise plumbing. In contrast to the West Virginia incident, hot water flushing was not recommended in Washington, D.C. and the flushing duration differed.[7] In Glendive, Montana hot water flushing was recommended and flushing duration was longer as compared to guidance issued in West Virginia and Washington, D.C. Moreover, indoor air monitoring in Montana revealed elevated volatile organic contaminant (VOC) levels when faucets were flowing.[8] In contrast to previous incidents, Montana residents were advised by officials to ventilate their premises while flushing.[9] It remains unclear what rationale was used to develop these three disparate approaches.

The ability of a premise plumbing flushing process to remove organic contaminants should be controlled by the system's configuration, its components, as well as the presence of system specific variables such as sediment, scale,

biofilm, and contaminant properties. Fig. 1 shows a typical trunk and branch premise plumbing design for a two story residential home with traditional storage water heating. The average single family U.S. residence has about 280 feet (ft) [85.3 meters (m)] of plumbing pipe (140 ft, or 42.7 m, each for hot and cold water) and uses an average of 180 gallons per day (gpd) [681.3 liters per day (L per day)].[10] Cold and hot water supply pipes generally range from 0.25 in [0.64 cm] to 0.75 in [1.9 cm] diameter in residences. Copper is the most common metal plumbing pipe used for cold and hot potable water supply, though a variety of plastic pipes are increasingly being installed (Table 1).[11]

Water heaters are a core component of premise plumbing, but are extremely complex as there are a wide variety of heater types and plumbing configurations that could influence the flushing process. For example, residential storage-type water heaters generally range from 40–80 gallons (gal) [151.4–302.8 L] depending on power source and home size. Where space is restricted (e.g., mobile homes and apartments) storage tanks of 20–40 gal [75.7–151.4 L] are used.[12,13] Tankless water heaters store substantially less water (up to 2–5 gal [7.6–18.9 L] for point of use systems). Storage-type units with hot water recirculation are gaining popularity and are mandated in certain municipalities.[13] In newer buildings with hot water recirculation, water age increases and contaminants can remain in premise plumbing substantially longer.[14,15]

Previous studies have shown that flow velocity and flow rate can impact contaminant removal efficiency during flushing.[16,17] These parameters can be affected by water saving devices and fixtures designed to minimize flow rate. New regulations have required bathroom faucets to have a maximum flow rate of 1.5 gallons per minute (gpm) [5.7 L min^{-1}], at 60 pounds per square inch (psi) and a minimum of 0.8 gpm
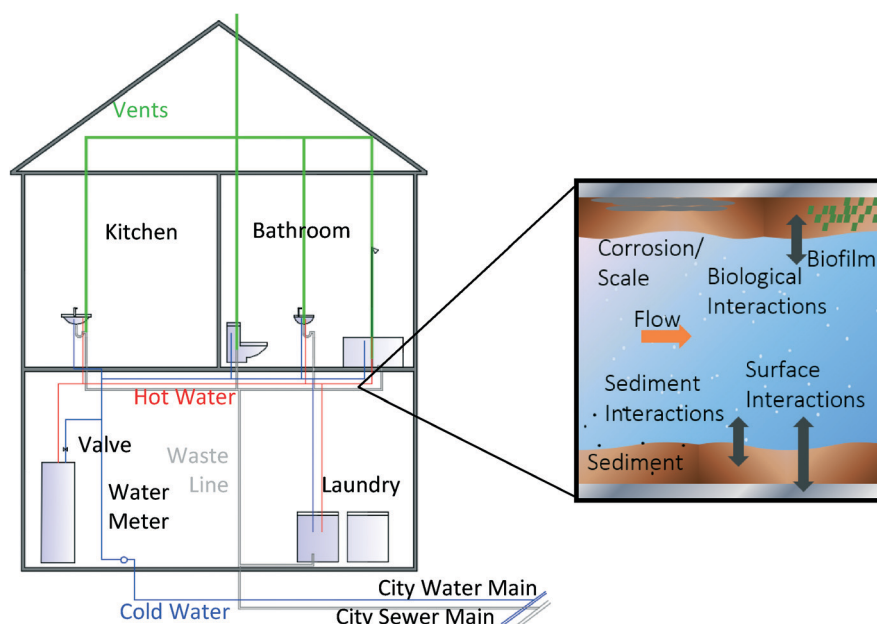

Fig. 1 Example premise plumbing layout for a residential home with a standard water heater that does not re-circulate.

Table 1 Types of potable water plumbing system materials in new and old residential buildings

Component	Plastics	Other materials
Piping	Polyvinylchloride (PVC) High-density polyethylene (HDPE) Crosslinked polyethylene (PEX) Polypropylene (PP) Chlorinated PVC (cPVC)	Copper, galvanized iron, concrete, lead, lead-lined steel, black steel, brass
Pipe coatings	Epoxy (EP) Polyurethane (PU) Polyurea (PEUU)	—
Faucets, valves, & fittings	Synthetic rubber (o-rings) PVC	Lead, stainless steel, brass, copper, aluminum
Gaskets	Ethylene–propylene–diene monomer (EPDM) [sulfur and peroxide crosslinked] Butyl rubber (BR) Natural butyl rubber (NBR) Styrene–butadiene rubber (SBR) Neoprene	—
Water heater	Polysulfone (PSU) dip tubes	Steel, glass, ceramic interior linings, Mg or Al sacrificial anode rod

[3.02 L min^{-1}] at 20 psi.[18] New faucet and showerhead aerators can also reduce flow rates by 40%.[19] New kitchen aerators have flow rates no greater than 2.2 gpm [8.32 L min^{-1}] and new bathroom faucet aerators restrict the flow from 0.5–1.5 gpm [1.9–5.7 L min^{-1}]. New standard, low flow, and ultra-low flow showerheads have flow rates between 1.2–2.5 gpm [4.7–9.4 L min^{-1}] (at 80 psi) compared to older showerheads where 4–5 gpm [15.1–18.9 L min^{-1}] was standard.[19,20] To flush the same volume of water from a new home with reduced fixture flow rates, longer durations may be required. Reduced flow rates can also be caused by plumbing corrosion and scale buildup.[21] As the authors discovered while investigating contaminated residential premise plumbing in West Virginia,[1] clogged or slow-draining outlets could result in failing to achieve a fixture's manufactured flow rate.

The premise plumbing component itself as well as its surface, scale, biofilm, and sediment could influence contaminant removal. Appurtenances such as fixtures, valves, fittings, along with gaskets and water heater components are comprised of a number of metals and plastics. Water heater tanks are generally glass lined, but often contain sediment, which can sequester and release contaminants.[22] Plastic materials are susceptible to permeation by organic chemicals[23–25,59] (*i.e.*, microcystins[26,27]), and contaminants can sorb into biofilms.[25,28] Contaminants may interact with surface deposits including, but not limited to, iron scale tubercles, manganese oxyhydroxides, calcium carbonate, aluminum hydroxide, and phosphate containing material.

This study was initiated because premise plumbing flushing caused illness following the January 2014 drinking water contamination incident in West Virginia and flushing procedures applied at subsequent organic contaminant incidents in Canada and the U.S. varied. The present study's aim was to review current knowledge associated with premise plumbing decontamination and create a rationale for science-based flushing protocols. The research objectives were to: 1) conduct a literature review to identify premise plumbing

decontamination approaches, 2) develop and apply a water heater decontamination model for the contamination incidents in West Virginia and Montana, and 3) identify future research needs. Organic chemical contamination incidents were the sole focus of this study.

Experimental methods

Literature review

Peer-reviewed literature, foundation and industrial reports, conference materials, as well as Canadian and U.S. government reports were analyzed. Incident causes, detected contaminants, and premise plumbing decontamination actions varied widely. To more clearly explain the findings, incidents were grouped into two categories: 1) water distribution contamination and 2) localized premise plumbing contamination. Contamination incidents were initially detected by drinking water consumer complaints, facility operator observations, and notification by first responders at the site of contaminant origination.

Water heater model

Model derivation and assumptions. When premise plumbing systems become contaminated, water heaters store a large volume of affected water. Removing this contaminated water is important prior to returning the plumbing system to service. A mass balance model was developed to evaluate water heater decontamination effectiveness for the 2014 coal washing liquid and 2015 crude oil drinking water contamination incidents in West Virginia and Montana. These events were evaluated because field data was available for modeling, unlike other incidents reviewed where little to no water testing records were found.

To predict each flushing protocol's efficacy in reducing water heater contaminant levels, an ideal water heater was modeled. The model was simplified using the following assumptions: (a) no contaminant reaction or degradation

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within the system (*i.e.*, a conservative pollutant), (b) no temperature dependence, (c) ideal mixing [$C(t) = C_{out}$], (d) the pollutant was already present and equally dispersed within the water heater [$C_0 \neq 0$], (e) no head loss, (f) all flow rates were equal [$Q_{in} = Q_{out} = Q$], (g) no interaction with the sediment present, and (h) no residual contaminant desorbed from plumbing components and entered the water. The derivation of the model was as follows:

$$\frac{dM}{dt} = Q_{in}C_{in} - Q_{out}C_{out} \pm rV$$

with the underlying assumptions, the equation simplifies to:

$$V\frac{dC}{dt} = QC_{in} - QC_{out}$$

integrating ($C(t) = C_{out}$):

$$C = C_{in} - (C_{in} - C_0)e^{-\frac{Q}{V}t}$$

where C is the concentration leaving the system (equal to the concentration within the water heater), C_{in} is the concentration entering the water heater, C_0 is the initial concentration within the water heater, Q is the flow rate, V is the tank volume, M is mass, and t is time. A diagram of the water heater model is displayed in Fig. 2.

Premise plumbing components and field data. Water heater decontamination was evaluated for two categories of residential buildings and four plumbing system types per category. The characteristics of the two residences selected were a 3 bedroom 1 bath manufactured home that contained 2 sinks (faucets) and 1 showerhead, and a two story single family home that contained 3 bedrooms and 2.5 baths with a total of 4 faucets and 2 showerheads. Water heater sizes examined were 20–40 gal [75.7–151.4 L] capacity for the manufactured home and 40–80 gal [151.4–302.8 L] capacity for the single family home.[12,13] The four plumbing system configurations examined were:
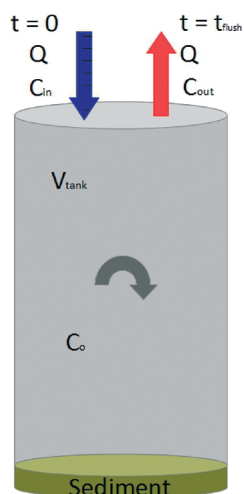

Fig. 2 Water heater control volume.

• Legacy home A: faucet flow rate 4 gpm [15.1 L min^{-1}] and 5 gpm [18.9 L min^{-1}] showerhead flow rate.
• Legacy home B: faucet flow rate 2 gpm [7.6 L min^{-1}] and 5 gpm [18.9 L min^{-1}] showerhead flow rate.
• Renovated home: faucet flow rate 1.5 gpm [5.7 L min^{-1}] and 2 gpm [7.6 L min^{-1}] showerhead flow rate.
• New home: faucet flow rates of 0.8 gpm [3 L min^{-1}] and 1.25 gpm [4.7 L min^{-1}] showerhead flow rate.

A condition of the modeling was that all fixtures in each home were flushed simultaneously, which is referred to as conventional flushing. Contaminated water stored in service lines, plumbing pipes, valves, and fixtures was not considered in the flushing model.

Flushing duration as well as initial and influent water heater contaminant concentration assumptions differed between the West Virginia and Montana model runs. In West Virginia, the utility advised residents to flush all of their hot water taps for 15 minutes "to bring MCHM [4-methylcyclohexanemethanol] levels under the 1 ppm [mg L^{-1}] standard established by the U.S. CDC [Centers for Disease Control and Prevention]".[29] 4-MCHM was the main ingredient in the coal washing liquid that contaminated the drinking water. The State of West Virginia also recommended residents conduct hot water flushing first for 15 minutes for buildings that discharged to septic systems. The initial 4-MCHM water heater concentration (C_0) chosen for the model herein was 3.773 mg L^{-1}, the greatest known 4-MCHM concentration in the utility's water distribution system.[2] For the West Virginia incident, water heater decontamination scenarios were evaluated using ten different influent 4-MCHM concentrations (C_{in} values of 0.017 mg L^{-1} to 0.319 mg L^{-1}), representing the maximum 4-MCHM concentration observed in the water distribution system during each day following the lifting of the "Do Not Use" drinking water order.[1]

To evaluate water heater decontamination in Montana, a 15 minute flushing duration was also applied. The initial benzene concentration (C_0) in the water heater was 15 µg L^{-1}, the maximum concentration found at fire hydrants.[30] The U. S. Environmental Protection Agency (EPA) drinking water maximum contaminant level (MCL) for benzene [5 µg L^{-1}] was used for evaluating flushing effectiveness. No water testing results were found that described premise water quality after residents were directed to flush. As a result, the C_{in} for Montana was assumed to be 0 µg L^{-1}.

Results and discussion

Literature review: building plumbing system contamination

The literature review revealed that flushing with and without chemical oxidation and surfactant aides has been applied in response to organic contaminant drinking water contamination incidents. Thirty-nine intentional and unintentional drinking water chemical contamination events from the past 40 years were found. Contaminants, some described in detail and others rather vaguely described in the literature, had a

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wide range of physiochemical properties (Table SI-1†). For the previously discussed 2014 incident in West Virginia, one research team identified additional chemicals present in the contaminated drinking water that officials did not test for during the response.[31] This discovery implies that the limited water testing data available in the literature may not fully describe the effectiveness of premise plumbing flushing as some chemicals may have been overlooked.

Causes of drinking water distribution system and subsequent premise plumbing system contamination included leaking above ground chemical storage tanks, train derailments, cross-connections, and chemical pipeline failures. Many times contaminants entered a water distribution system after the source water became contaminated and contaminated water had passed through the water treatment plant. In contrast, localized premise plumbing system contamination incidents were caused from internal sources such as cross-connections and backflow issues involving negative pressures. When drinking water contamination originated from within the building, the radius of infrastructure affected was limited, but higher pollutant concentrations were sometimes observed.[32]

Water distribution systems. Premise plumbing systems have been contaminated with a wide variety of pollutants that entered the premise by way of the utility water distribution systems (Table 2). Some of the contaminants detected in the 21 incidents found included microcystins, benzene, toluene, ethylbenzene, xylenes, various other VOCs, pesticides, and unregulated semi-volatile organic compounds (SVOC) with a wide range of physiochemical properties. The six incidents that occurred in Canada and the U.S. since January 2014 had the greatest amount of publicly available data and were examined more closely.

In these six most recent cases, residents were without water from 3 to 30 days due to contamination. In premise plumbing contamination incidents prior to January 2014, building inhabitants were without safe water for up to several months, but outage duration often was not reported in incident reports. Restricted use orders for drinking water were issued in all six recent events. Population water use restrictions ranged from avoiding all water contact except for toilet flushing and firefighting activities, to only banning ingestion, boiling, and bathing activities. During all of these incident recoveries, contaminated water was flushed through fire hydrants and the public was advised to flush contaminated water out of their premise plumbing. No other decontamination approach such as chemical oxidation or surfactant use was applied.

Premise plumbing water testing results were found for only four of the six recent incidents, though the

Table 2 Building plumbing system contamination incidents where the source originated from outside the building

Location	Year	Cause	Contaminant	Plumbing system decon method	Population affected	Health impacts	Duration, days
Nibley City, UT[45]	15	Truck spill	Diesel fuel	Flushing	5000	nr	1
Glendive, MT[46]	15	Pipe rupture, spill	Crude oil	Flushing	6000	Yes	5
Longueuil, QC, CN	15	Tank rupture, spill	Diesel fuel	None	230 000	No	2
Washington, D.C.[47]	14	Unknown	Petroleum product	Flushing	Est. 370	nr	3
Toledo, OH[48]	14	Algal bloom	Microcystins[c]	Flushing	500 000	No	2
Charleston, WV[1]	14	Tank rupture, spill	Coal chemical	Flushing	300 000	Yes	9[b]
Jackson, WI[49]	12	Pipe rupture, spill	Petroleum product	nr	50	nr	30
Safed, Israel[38]	10	DS backflow	Diesel fuel	Flushing; surfactant	3000	nr	3
Boise, ID[50]	05	Unknown	TCE	Flushing	117	nr	nr
Stratford, ON, CN[51]	05	DS backflow	2-Butoxyethanol	Flushing	32 000	Yes	Up to 7
Northeast Italy[52]	02	New pipe install	Cutting oil	Flushing	4 bldgs	nr	Months
Guelph, CN[53]	97	DS backflow	Petroleum product	nr	48 000	nr	3
Charlotte, NC[36]	97	DS backflow	Fire suppressant (AFFF)[d]	Flushing	29 bldgs	No	nr
Tucumcari, NM[32,54]	95	DS backflow	Toluene, phenol, etc.[a]	Flushing	nr	Yes	nr
Uintah Highlands, UT[32]	91	DS backflow	TriMec; 2,4-D; dicamba	nr	2000 homes	Yes	nr
Hawthorne, NJ[36]	87	DS backflow	Heptachlor	Cl$_2$ flush; replacement	63	No	nr
Gridley, KS[54]	87	DS backflow	Lexon DF	nr	10 homes, 1 business	nr	nr
Hope Mills, NC[36]	86	DS backflow	Heptachlor, chlordane	Flushing	23 homes	No	3
Pittsburgh, PA[54]	81	DS backflow	Heptachlor, chlordane	Flushing; replacement	300 (23 bldgs)	No	27
Lindale, Georgia[55]	80	DS construction	Phenolic compounds	Super-chlorination	Hospital	Yes	nr
Montgomery Cnty, PA[35]	79	Tank rupture, spill	TCE	nr	500	Yes	nr

TCE = trichloroethylene; nr = not reported in the literature; DS backflow represents back-siphonage of liquid through a fire hydrant or existing water distribution system connection.[a] Benzene, ethanol, nonanoic acid, decanoic acid, octanol, octanoic acid, heptanoic acid, butanoic acid, silicone, diconic acid and four trihalomethanes. [b] Some residents waited 30 days before flushing the contaminated water from their premise plumbing. [c] Microcystins present were estimated to include LR (60–80%), RR (10–25%), and YR (5–15%). [d] Aqueous-film forming foam.

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representativeness of the data may be questionable. In West Virginia, utility and state officials collected drinking water from businesses and government buildings. However, these officials flushed cold water taps for 15 minutes prior to collecting samples in an effort to obtain water from the utility water distribution system rather than the premise plumbing system. Several nonprofit, for-profit, and university research teams did conduct testing of premise plumbing water (first-draw samples).[1,4] Officials did not use this information for premise plumbing flushing decisions or monitoring protocol effectiveness. Premise plumbing water testing data were found in Montana before flushing, but no water testing data were found representative of premise water quality after flushing. Premise drinking water testing data before and after flushing for the other recent incidents was also lacking.

While many incident reports lacked premise drinking water quality data pertaining to flushing effectiveness, a few incident reports prior to 2014 contained detailed information. For example, when pesticides contaminated plumbing systems in Pennsylvania (1981) and New Jersey (1987), flushing was unable to reduce contaminant levels below acceptable exposure limits. In Pennsylvania, hot water was found to have significantly greater pesticide concentrations than cold water during flushing implying that hot water plumbing components, sediment, and corrosion products had sequestered contaminant.[33,34] When flushing could not reduce contaminant levels successfully, premise service lines and plumbing components were replaced.[35,36] In one case, plumbing pipes were super-chlorinated after flushing in an attempt to degrade the remaining chemicals, but this technique was not effective.[36] Premise plumbing decontamination using oxidants has not been widely applied, but was found effective for certain utility water distribution system-chemical contamination scenarios in Europe.[37] A water distribution system contamination incident in Israel was also examined. In response to this incident, flushing with use of a surfactant was used to remediate the water distribution system.[38] Surfactants have not been widely applied in premise plumbing decontamination activities.

Localized building events. Premise plumbing contamination caused by a source inside the building represents a large group of underreported, high risk contamination events. Numerous cross-connection control trade associations have been established to raise awareness about the risks these incidents pose to public health. For several decades, there have been a significant number of incidents documented that involved the accidental backflow of ethylene glycol, a common compound used in heating ventilation and air conditioning systems, into premise plumbing (Table 3). In many of the cases, an open valve, whether by mistake or malfunction, in combination with negative pressure often occurring from repairs introduced organic chemicals into premise plumbing. These negative pressure events, common in water distribution systems, are typically caused by a significant change in water velocity[39] and can lead to under-identified contamination incidents.

Analysis of flushing procedures across incidents. Flushing is a common approach to removing contaminated water from premise plumbing. There is, however, wide disparity between procedures, and evidence shows that poorly designed flushing procedures can cause building inhabitants to become ill. Of the premise plumbing contamination responses identified, 19 used flushing as the primary decontamination technique, three combined flushing with chlorination, and one used flushing in combination with a surfactant. Only ten incident reports contained flushing guidance that enabled a more detailed analysis (Table 4).

Table 3 Building plumbing system drinking water contamination incidents where the source originated from inside the building

Location	Year	Incident	Contaminant	Decontamination method	Population affected	Health impacts	Duration, days
Winnipeg, AB, CN[53]	06	A/C backflow	Cooling sys liquid	Flushing	430	No	nr
Florida[56]	01	A/C backflow	Ethylene glycol	nr	School	Yes	nr
Franklin, NE[54]	94	A/C backflow	Freon	nr	nr	Yes	nr
Superior, AZ[36]	93	Fire system backflow	Propylene glycol	Flushing; chlorination	Park	Yes	nr
Missouri[54]	91	Backflow	Trichloroethane	Flushing	nr	nr	nr
Brighton, CO[54]	90	A/C backflow	Ethylene glycol	Flushing	450	Yes	nr
Tucson, AZ[32]	89	Backflow	Diazinon	nr	nr	No	nr
Cincinnati, OH[54]	89	A/C backflow	Algae retardant	nr	Office building	Yes	nr
Medicine Hat, SK, CN[53]	89	Boiler backflow	Ethylene glycol	nr	Residential building	Yes	nr
Edgewater, FL[54]	88	Backflow	Ethylene glycol	Flushing	Factory	No	<1
Cleveland, OH[54]	88	Backflow	Water-soluble oil	nr	6 families	nr	nr
North Dakota[54]	87	A/C backflow	Ethylene glycol	nr	Building	Yes	nr
Kansas[54]	86	Backflow	Malathion	nr	Grain mill	Yes	nr
New York[54]	85	A/C backflow	Ethylene glycol	nr	Hospital	Yes	nr
Boston, MA[54]	85	Backflow	Ethylene glycol	Hydrants and taps flushed	Hospital	nr	nr
Macon, GA[54]	84	Backflow	Creosote	Flushing	nr	Yes	0.83
Woodsboro, MD[54]	83	Tank backflow	Paraquat	Flushing	nr	nr	nr
Bailey, CO[57]	82	Faulty valve	Ethylene glycol	Flushing	300	Yes	2

nr = result not reported in the literature; A/C = air conditioning system.

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Table 4 Flushing procedures explained in the literature differed based on the sequence of flushing activities, premise flushing locations, and duration[a]

Location, date	Contaminant	In-home flushing procedure
Nibley, UT, 2015	Diesel fuel (SVOCs, VOCs)	Cold water 35 min, hot water 30 min, run appliances, continue until odor gone[58]
Glendive, MT, 2015	Crude oil (metals, SVOCs, and VOCs)	Cold water 20 min, hot water 15 min (ref. 9)
Washington, D.C., 2014	Estimated to be a petroleum based solvent (contaminants unknown, Possible SVOCs and VOCs)	Begin at the sink on the lowest floor and run each cold water tap 10 min, flush cold water from upper level sinks 5 min, refrigerator water dispenser 5 min (ref. 7)
Toledo, OH, 2014	Microcystins	Hot water 15 min, cold water 5 min, appliances 5 min (ref. 48)
Charleston, WV, 2014	Crude MCHM, stripped PPH (SVOCs, VOCs)	Utility: hot water 15 min, cold water 5 min, appliances 5 min (ref. 2) health dept: hot water 13 min per faucet, starting in kitchen. 2 min all hot water faucets. Cold water 4 min per faucet, 1 min all cold water faucets. Attempt to discharge to ground surface instead of septic tank
Stratford, ON, CN, 2005	Car wash cleaning agent containing 2-butoxyethanol (possible VOCs)	Cold water 5 min (ref. 51)
Charlotte, NC, 1997	Fire suppressant (AFFF) – hydrocarbon based surfactant	Hot water 10 min, cold water 10 min (ref. 36)
Los Angeles, CA, 1994	Macrojet concentrate	Flush both hot and cold water[54]
Hope Mills, NC, 1986	Pesticide (heptachlor, chlordane) (possible VOCs)	Flush to drain lines and water heaters[36]
Macon, GA, 1984	Creosote (VOCs present)	Flush plumbing for 30 min (ref. 36)

[a] Chemical composition not found.

There was little uniformity in premise plumbing flushing procedures. Recommendations varied widely for flushing duration, the flushing stepwise process (all fixtures flushed simultaneously or in a staged approach), if and in what order hot and cold water lines should be flushed, if drinking water odor should be used as an end point, and if indoor ventilation precautions were issued and the specificity of those precautions (Fig. 3 and Table 4). Additionally, several premise plumbing flushing protocols did not seem to include the time needed to remove contaminated water from residential
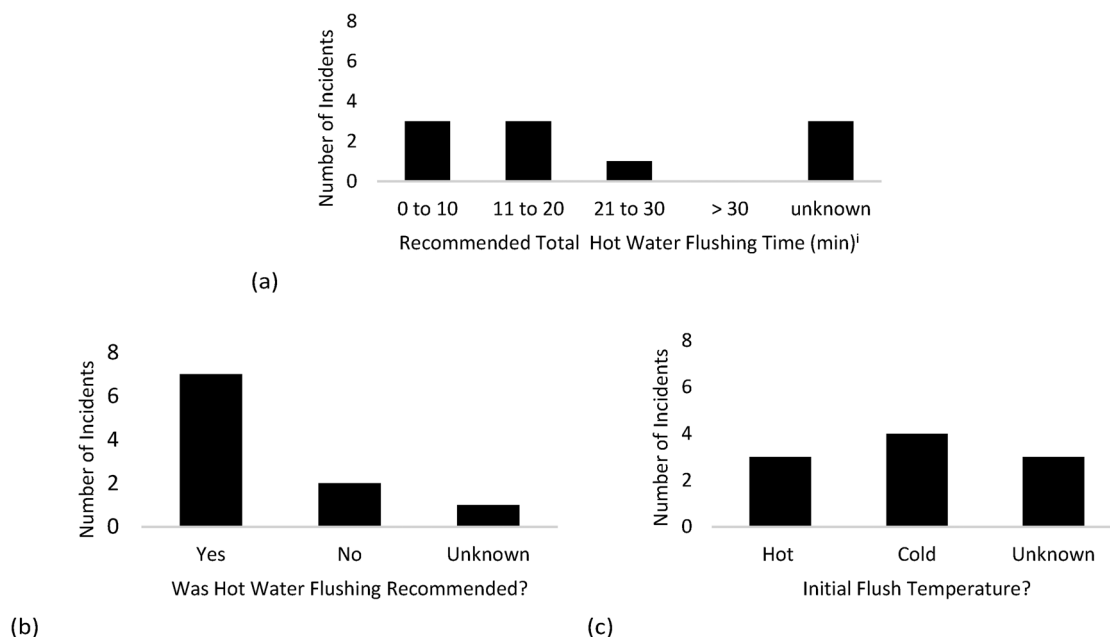

Fig. 3 Comparison of premise plumbing system flushing guidance for ten incidents. (a) Recommended hot water total flushing time, (b) number of incidents where residents were explicitly directed to flush hot water, (c) recommended water temperature for the initial flush. Incidents represent those events presented in Table 4. [i]West Virginia septic tank flushing procedure not included.

service lines. For example, the World Health Organization (WHO) explained 2–10 minutes of flushing was needed for the service line, but also cautioned that this duration this may not be sufficient to fully flush the line due to variable service pipe lengths.[40] Others have found that a 15 minute flush was required to remove water from residential service lines.[13] By flushing hot water first it seems several flushing protocols likely replaced contaminated water in the water heater with equally contaminated water from the service line.

Model: water heater decontamination

Several water heater decontamination scenarios were found where flushing did not reduce contaminant levels below the health based drinking water limits in West Virginia and Montana (Tables SI-2–SI-7†). These scenarios were based on 1) flushing guidelines issued by the officials, 2) maximum contaminant concentrations found within the contaminated utility water distribution systems, and 3) common water heater sizes, fixture types, and flow rates presented in the experimental methods section.

The water utility and State of West Virginia flushing guidelines were examined for the West Virginia incident. Because the total flushing durations of each protocol were the same, the impact of flushing on water heaters by both protocols can be discussed singularly. The model revealed several water heater flushing scenarios where the 4-MCHM concentration was not reduced below the CDC's health limit (Tables SI-2–SI-5†). Of the 120 scenarios modeled for the manufactured home, 14 did not reduce 4-MCHM concentrations below the CDC limit. For the two story single family home, 24 scenarios of 200 examined did not result in a 4-MCHM concentration below the CDC limit. The water heater influent

concentration, storage tank volume, and flow rate were responsible for these exceedances (Fig. 4).

Water saving devices also limited the ability of the flushing process to reduce the 4-MCHM water heater concentration and the larger the water heater volume, the more likely the flushing process did not achieve its objective. The total water heater flushing duration necessary to reduce the 4-MCHM concentration below the CDC limit (with several influent concentrations) varied from 2 minutes to upwards of 22.8 minutes depending on water heater volume and flow rate (Table 5).

The flushing duration needed to reduce the 4-MCHM concentration in the water heater by 90%, 99%, and 99.9% was also calculated. The model showed that even under the best-case scenario (smallest water heater size, highest flow rate), a 3-log removal (99.9%) could not be achieved within 10 minutes (Table 6 and SI-9†). A 3-log removal of 4-MCHM, 3.773 mg L^{-1} to 3 μg L^{-1}, assuming C_{in} was zero, would have required 97 minutes. Unfortunately, for this case the drinking water would still have had a detectable licorice odor as odor threshold concentration was less than 0.15 μg L^{-1}.[41] Also, the flush water was contaminated with as much as 0.319 mg L^{-1} 4-MCHM.

In contrast to model results from the West Virginia incident, only 2 scenarios of 32 examined for the Montana crude oil contaminated water incident resulted in benzene exceeding the drinking water health limit (Fig. 5). These Montana scenarios (one for the two story single family home and one for the manufactured home) involved buildings with water saving fixtures and the largest size water heater. A limitation of the Montana modeling effort was that no post-flushing premise drinking water quality test results were found to validate the model.
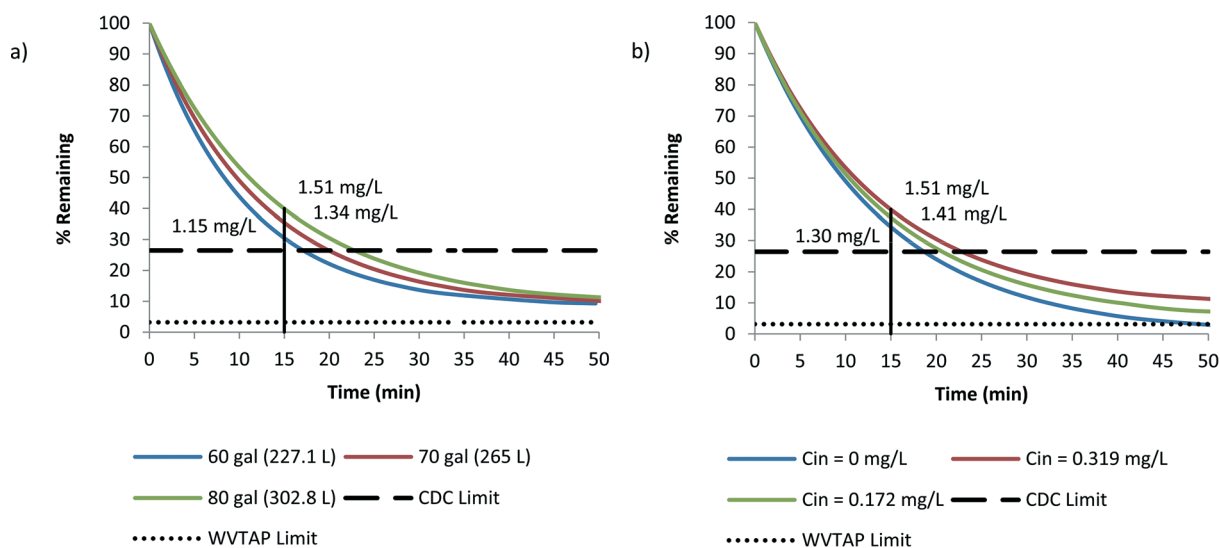

Fig. 4 West Virginia example: new two story single family home with water saving fixtures, initial 4-MCHM concentration of 3.773 mg L^{-1}. (a) with tank volume 60–80 gallons [227.1–302.8 liters] and influent concentration 0.319 mg L^{-1}, (b) with tank volume of 80 gallons [302.8 liters] and variation of influent concentration 0–0.319 mg L^{-1}. CDC and WVTAP health based screening levels were 1 mg L^{-1} and 0.120 mg L^{-1}.

Table 5 Flushing duration needed to reduce the 3.773 mg L^{-1} water heater 4-MCHM concentration to the CDC's 1 mg L^{-1} drinking water screening level, minutes

Influent concentration, mg L^{-1}	Plumbing system type			
	Legacy A	Legacy B	Renovated	New
0	2.0–4.1	3.0–5.9	5.3–10.6	9.3–18.6
0.01	2.1–4.1	3.0–5.9	5.3–10.7	9.4–18.7
0.10	2.2–4.3	3.1–6.3	5.6–11.3	9.9–19.7
0.20	2.3–4.6	3.3–6.7	6.0–12.0	10.5–21.0
0.319	2.5–5.0	3.6–7.2	6.5–13.0	11.4–22.8

Table 6 Time needed to achieve 1-, 2-, and 3-log removal from a water heater in a two story single family home assuming no chemical interaction, degradation, or source

Water heater size (gal)	Type	Log removal time (min)		
		1	2	3
40	Legacy A	3.5	7.1	10.6
	Legacy B	5.1	10.2	15.4
	Renovated	9.2	18.4	27.6
	New home	16.2	32.3	48.5
50	Legacy A	4.4	8.9	13.3
	Legacy B	6.4	12.8	19.2
	Renovated	11.5	23.0	34.5
	New home	20.2	40.4	60.6
60	Legacy A	5.3	10.6	15.9
	Legacy B	7.7	15.4	23.0
	Renovated	13.8	27.6	41.5
	New home	24.2	48.5	72.7
70	Legacy A	6.2	12.4	18.6
	Legacy B	18.6	37.1	55.7
	Renovated	16.1	32.2	48.4
	New home	28.3	56.6	84.8
80	Legacy A	7.1	14.2	21.3
	Legacy B	10.2	20.5	30.7
	Renovated	18.4	36.8	55.3
	New home	32.3	64.6	97.0

1-, 2-, and 3-log removal constitutes 90%, 99%, and 99.9% reduction of contaminant concentration.

Limitations and implications

This study has several limitations, but provides a foundation from which premise plumbing decontamination approaches can be further developed. Absence of flushing protocol design information and premise plumbing water quality testing data for the incidents reviewed inhibited the authors from fully examining how utilities and public health agencies developed and validated flushing protocol effectiveness. Results showed that premise plumbing design, operational conditions, contaminants present and their properties, as well as building inhabitant safety have not been fully considered in the design of previous flushing protocols. No formal guidance was found on how to remediate premise plumbing contaminated by organic chemicals. In light of recent large-scale drinking water contamination incidents as well as economic, social, and public health impacts they caused, additional research on premise plumbing decontamination is very much needed.
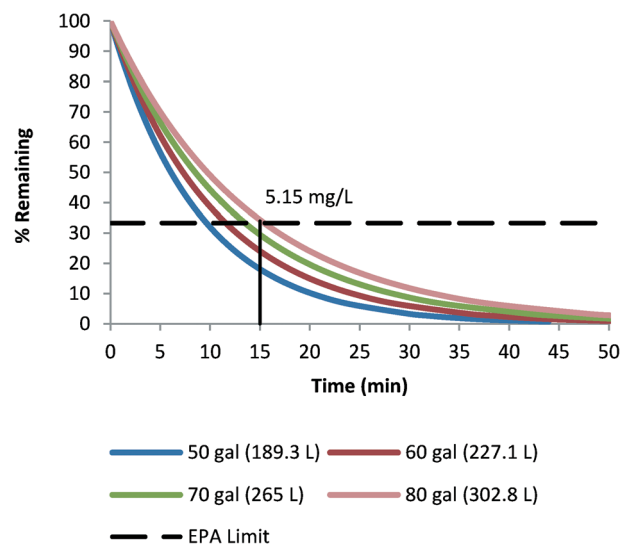

Fig. 5 Montana example: new two story single family home with water saving fixtures, initial benzene concentration of 15 μg L^{-1}, and EPA MCL of 5 μg L^{-1}.

Flushing is a common technique applied in the pharmaceutical, food and beverage, and chemical production industries. In these industries, flushing is applied to remove contaminated liquid from piping systems and contaminants from surfaces. Best practices from these disciplines should be considered in the design and selection of premise plumbing decontamination methods. Flushing has proven to be an effective premise plumbing decontamination technique, but there have been some instances where it has failed and component replacement was required.[33] For example, flushing was unable to decontaminate pesticides in the premise plumbing. Because premise drinking water data was lacking for the majority of incidents reviewed, the performance of other flushing protocols remain unclear.

An important observation is that while at least 15 minutes of flushing is needed for clearing some service lines,[12,13] several flushing protocols only required approximately 15 minutes of flushing duration. Also, hot water flushing was recommended as the first step for several of the flushing protocols. In these cases, equally contaminated water in the service line likely was drawn into the water heater. More work is needed to understand the volume of water stored in premise plumbing components as well as which premise plumbing contamination scenarios warrant more aggressive recovery methods. These methods include surfactant use and component replacement.

To enable utilities and public health agencies to rapidly and safely decontaminate affected plumbing systems, tools that can predict organic contaminant fate and removal effectiveness are needed. No literature was found for estimating organic contaminant fate in premise plumbing where a wide variety of designs and components exist. For an ideal situation, in the absence of oxidants, biofilm, rough pipe wall surfaces, and sediment in the water heater, contaminant fate will be influenced by physicochemical properties, water

chemistry, environmental conditions, and plumbing materials it contacts. Premise plumbing has been contaminated by contaminants with a wide range of physiochemical properties: vapor pressure (10^{-7} to >7542 mmHg), water solubility (0.01299 mg L^{-1} to miscible), log K_{ow} (−1.36 to 6.26) (Table SI-1†). Should contaminants react with oxidants, interact with biofilms, pipe wall surfaces, surface deposits, or water heater sediment, describing their fate, and that of their degradation products, would be much more complex. While flushing can be sufficient for bulk contaminant removal, this process may not remove pipe deposits or films.[42] Scouring and physical removal of sediment, sorbed surface substances, and scale material may also be needed. While some surface scales can be easily removed such as a thin scale of manganese on PVC pipe,[43] researchers have found that several organic contaminant-pipe deposit pairs can be highly problematic to remediate. For example, acetonitrile was needed to extract certain organic contaminants from utility water distribution system biofilms and clay deposits.[37] Research is needed to understand contaminant fate in premise plumbing. Results can aide utility and public health agencies in their infrastructure decontamination decisions.

The flushing guidance issued by the utility in West Virginia explicitly stated "after you have flushed each hot water faucet for 15 minutes, your water heater will be safe for use".[2] The water heater model predicted several premise plumbing design and operation scenarios in West Virginia where 4-MCHM levels were not reduced below the CDC drinking water screening level. This guidance did not take into account the time needed to clear contaminated water from service lines (15 minutes required[12,13]) and hot water lines within residence piping (6.5 gal [24.6 L] for the average home[14]) before water heater flushing was conducted. As a result, the water may not have been safe to use after building inhabitants completed the flushing procedure. An important note is that at least one other coal washing contaminant was found by researchers in the drinking water, which was not considered in either water distribution system monitoring or flushing protocol design.[29] As a result, the proposed model may have overestimated how well residential water heaters were decontaminated; more hot water flushing scenarios could have failed to reduce contaminant levels below acceptable exposure standards. Bench-scale data are needed to further test the water heater model presented herein. Field data should be collected when premise plumbing flushing processes are carried-out in response to future contamination incidents.

Flushing protocol design and future research. The ultimate goal of decontamination should be for building inhabitants to regain safe use of their plumbing systems. To this end, it is important that utility and public health agencies not only understand the contaminants and concentrations present and their toxicity, but also communicate with one another about the decontamination goal and the acceptable concentration of contaminant(s) permitted in premise plumbing. Confusion about what constitutes safe drinking water can influence how the public evaluates premise plumbing decontamination. A sequence of events during 2014 West Virginia chemical spill response provides insight into this challenge.[1]

• January 9 the CDC issued a health based 1 mg L^{-1} 4-MCHM drinking water screening level. Later that day the state determined the 4-MCHM screening level should be 10 µg L^{-1}.[44]

• January 10 the U.S. Agency for Toxic Substances and Disease Registry advised the state to flush the affected water system until the drinking water's licorice odor was no longer detectable (<0.15 µg L^{-1}).

• January 13–18 the public was directed to flush their premise plumbing systems.

• January 15 the CDC recommended pregnant women consider an alternate water source until 4-MCHM was nondetectable; method detection limit 10 µg L^{-1}.

• January 21 the company responsible for the chemical spill disclosed to the water utility and state additional chemicals were present, propylene glycol phenyl ether and dipropylene glycol phenyl ether. These were then detected in the drinking water, but not considered in the flushing protocol.

While the mechanics of premise plumbing flushing are important, it is also important that the target contaminant(s) and concentration(s) are well-justified, publicly defined, and are used to define the premise plumbing remediation procedure.

Until a more fundamental understanding of plumbing system decontamination can be developed, water utilities and public health agencies could consider the following approach. The ideal case is when the water distribution system has been fully decontaminated and water free of the contaminant(s) [concentration = 0] will be used for premise plumbing decontamination. Though, as shown in prior incidents, some residual level of contaminant may be present in the distribution system. Premise plumbing flushing procedures should consider the presence of residual contaminant when predicting flushing effectiveness.

A staged or conventional flushing approach should be considered. Staged flushing is where the location closest to the service line is flushed first, then fixture flushing is conducted sequentially throughout the building to prevent the spread of contamination further into the plumbing system. Staged flushing may also be called unidirectional flushing. Conventional premise plumbing flushing is where all fixtures are flushed simultaneously.

Before flushing begins, several site preparation activities should be considered. Low-flow conditions and devices should be addressed. Aerators could be removed from fixtures to allow for elevated flow rates. Point-of-use and point-of-entry devices should be removed from premise plumbing. This is especially important before flushing begins so flow restrictions and potential contaminant sources within the plumbing system are removed. Disposal of the removed materials (*i.e.*, faucet water filters, softener resin) exposed to the contaminated water should be considered.

Building inhabitant safety is a critically important aspect of the flushing process. For situations where organic contaminants do or might pose inhalation risks, models should be developed and applied to estimate indoor air chemical exposure during the flushing procedure. The models should also be run to estimate the exposure to the most sensitive population (*i.e.*, infants, children, persons with respiratory disease, *etc.*), who, unless directed to leave the premise, will be present during flushing. Under situations where drinking water contaminants are volatile and there is little toxicological data available, building inhabitants should be advised to evacuate the buildings during flushing and additional personal protective equipment (PPE) is recommend. In the field, windows and doors could be opened and fans could be setup to expel contaminated air. The contaminated water's chemical composition should be well defined so that the target contaminants, concentrations, and possible safety issues are thoroughly understood during flushing protocol design.

Once the site has been prepared, flushing could start at cold water tap closest to the service line. Current guidance indicates at least 15 minutes is required to flush residential service lines. With additional research into pipe diameters, lengths, and flow rates, this 15 minute flushing duration could increase or decrease. Next, cold water flushing could continue and start at the fixtures closest to the service line, then continue moving away from this point into the building. Fixtures located on the highest floor would be flushed last. Flushing of hot water lines and the water heater could be conducted after cold water lines have been cleared. Flushing guidance for appliances, outdoor spigots, and additional fixtures should also be considered.

Shutting off the water heater and draining its cooled water could be considered. This action would reduce the potential that hot contaminated water would be discharged into the home enabling chemical volatilization and pose inhalation and dermal contact risks to building inhabitants. Water heater draining should remove a large volume of contaminated water within the plumbing system and reduce the amount of this water that travels through building pipes and exits faucets. Water heater draining may also result in sediment discharge, and remove contaminant(s) that had sorbed to this material. This approach however should be carefully considered as draining water heaters may require special ventilation conditions and PPE. Handling and disposal of the discharged sediment should also be considered.

Because there is minimal flushing protocol performance data, it is recommended that flushing be conducted liberally where multiple cycles of flushing are carried-out rather than a single flushing event. Sending contaminated water into the premise wastewater collection system is one disposal option. In response to some incidents, contaminated water discharge onto the ground was recommended. The toxicity of the contaminated water, water volume, and water reuse potential must be considered in these situations. Damage to downstream wastewater collection and treatment assets, as well as the public and environmental health risks posed by water

should be considered. Coordination of premise plumbing flushing activities with the utility would be necessary, as a finite amount of drinking water is stored in the water distribution system. Efforts should be made so that enough water volume and pressure is available for flushing and other activities (*i.e.*, firefighting).

Before the flushing procedure is distributed to the affected population, water heater modeling, indoor air modeling, as well as water storage calculations, should be carried-out and the flushing procedure could be piloted in select buildings. Water testing before, during, and after flushing can help officials gauge whether or not the flushing approach has been effective. As researchers discovered in West Virginia, some premise plumbing drinking water 4-MCHM concentrations were unchanged or increased due to flushing.[1,4] Pilot testing of the flushing procedure could provide these or other insights (*i.e.*, chemical volatilization, sorption). Bench-scale studies could then be commissioned to better understand contaminant fate in plumbing systems (*i.e.*, sorption, degradation).[1,4]

The lack of published calculations explaining how flushing procedures were determined inhibited a more thorough examination of past incidents. The water heater model presented and study recommendations provide a first step in developing science-based decontamination protocols for varied plumbing systems. At present, a science-based approach for recovering from premise plumbing system chemical contamination incidents is lacking. There is much opportunity in this field for future advancement. Further development of an evidence based methodology for premise plumbing decontamination is very much needed.

Acknowledgements

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