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Feasibility of an environmentally friendly method of contaminant flushing in water distribution systems using containment ponds

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ABSTRACT

Water distribution system flushing is one way to get rid of contamination. In conventional flushing, all the contaminated water is discharged to the environment, thereby harming it. A new method is proposed here as an alternative solution, in which a containment pond lined with impermeable material will be constructed in a suitable place within the municipality. Network modelling was performed to investigate the feasibility of the new method. It was found that (1) the proposed flushing method can successfully reduce environmental impacts compared to hydrant flushing only, (2) a containment pond cannot clear the system periphery away from the containment pond, (3) the best location of a containment pond is not always at the furthest location from the source reservoir, and (4) for some systems, some pond locations might be better from an economic perspective, while other locations will be better environmentally.

Key words: contamination, environmental impact, infrastructure, public health, water supply

HIGHLIGHTS

- Containment ponds for water system flushing can successfully reduce environmental impacts by up to 100%.
- A pond cannot clear an entire system with numerous dead ends.
- The best location of a pond is not always at the furthest location from the source reservoir.
- A pond location tradeoff between cost and environment can exists for some systems.

INTRODUCTION

A water distribution system (WDS) is the physical network of pipes that delivers water from the water source to the intended users. Typically, this is achieved by pumping water from the source or reservoir, transporting it through the watermains and service pipes, and storing it in the elevated storage tank/s used for storage to handle fluctuating user demand. Valves and hydrants are secondary components of a WDS, where valves are used for controlling water flow and hydrants are for emergency situations like firefighting or contamination flushing (Viessman *et al.* 1998; Mays 2000; Wu 2015). The main purpose of a WDS is to deliver safe and uninterrupted drinking water to the users (Rasekh & Brumbelow 2013). However, contamination intrusion in the WDS is not an uncommon event (Hrudey & Hrudey 2004; Craun *et al.* 2006; Hrudey & Hrudey 2007; Seth *et al.* 2016). Any WDS can get contaminated both by intentionally introduced chemicals like chloride or fluoride or undesirable introduction of salt, lead, arsenic, or emerging contaminants from surface or ground water. Physical deterioration of the WDS components or equipment can also induce contamination (Rasekh & Brumbelow 2013).

In addition to accidental or intentional WDS contamination, saltwater intrusion is important in the coastal areas as a result of overextraction of water from freshwater aquifers. Overextraction of freshwater initiates sea water to seep through the aquifer (Edwards *et al.* 2009; Gleeson *et al.* 2012; Doell *et al.* 2014; Spellman 2017). This is now considered to be a significant threat to the drinking water quality of many coastal areas including Los Angeles (Edwards & Evans 2002; Spellman 2017), Georgia, northeastern Florida (Spechler 2001; Czajkowski *et al.* 2018), southwestern Nigeria (Ayolabi *et al.* 2013; Yusuf & Abiye 2019), Tamilnadu of India (Gopinath *et al.* 2016), and coastal areas of Bangladesh (Faneca Sànchez *et al.* 2015;

National University of Singapore 2020). Saltwater is not removed in the water treatment process and then is pumped into the distribution system.

Although contamination intrusion in a WDS is not a frequent incident, quick detection and proper management are important to protect community health (Poulin *et al.* 2010; Seth *et al.* 2016). Most contaminants spread rapidly through the distribution networks. At any contamination event, contamination detection is very difficult and nearly impossible to treat (Khanal *et al.* 2006; Seth *et al.* 2016). So, when a system becomes contaminated and treatment is not convenient, system flushing is a common way to get rid of contamination (Friedman *et al.* 2002; Shafiee & Berglund 2017). Usually, two techniques for flushing are used for WDS decontamination: conventional and unidirectional. In conventional flushing, opening of fire hydrants (usually one by one) can be sequential or non-sequential with no valve operation and eventually can fail to remove the contamination entirely from the system due to lack of adequate velocity within the pipes. In unidirectional flushing, fire hydrants are opened in a sequential manner, while the pressure valves on the consumers' sides are kept closed to ensure sufficient velocity. The recommended range of velocity for this flushing technique is 0.8 m/s (2.5 ft/s) to 3 m/s (10 ft/s) depending on the size of the utility and the type of the contaminant to be removed (Antoun *et al.* 1999; Shah *et al.* 2001; Hasit *et al.* 2004; Walski *et al.* 2008; Martin & Ries 2014; Wu 2015; Xie *et al.* 2015). Compared to conventional flushing, the use of water can be reduced by up to 40% using unidirectional flushing, however this technique also involves some constraints e.g., labor, time allocation, and proper management. Continuous blow-off is another flushing technique especially for stagnant areas of a WDS e.g., dead ends or large-sized pipes. Unfortunately, this method is not considered to be durable in general as typical velocity values obtained in this flushing technique are less than 0.3 m/s (1 ft/s) which is not sufficient to remove all types of contaminants (Oberoi 1994; Antoun *et al.* 1999; Hasit *et al.* 2004; Barbeau *et al.* 2005; Rebolledo *et al.* 2020). A routine flushing program is also followed in some water systems to maintain the water quality where the frequency of flushing can be monthly, quarterly, semiannually, annually, or seasonally. The frequency is selected based on the size of the system in addition to the susceptibility of the system to any chemicals, corrosion, high level of disinfectant residual, sediment accumulation, and/or customer complaints (Friedman *et al.* 2002; MELCC 2019).

Comparative studies have been performed on existing flushing methods including the use of aggressive flushing for identifying discoloration factors (Boxall *et al.* 2003), modelling of sediment in WDSs using unidirectional flushing (Carrière *et al.* 2005), evaluation of flushing to remove contamination (Polychronopolous *et al.* 2003; Vitanage *et al.* 2003; Poulin *et al.* 2010), modelling of a contamination events (Haxton & Walski 2009), planning and optimization of unidirectional flushing (Deuerlein *et al.* 2014), optimization of hydrant selection for conventional flushing (Wu 2015), mobile flushing to prevent secondary water contamination (Kowalski *et al.* 2015), valve management for improved water quality (Quintiliani *et al.* 2019), and changing of outflow to provide sufficient chlorine residuals (Avvedimento *et al.* 2020). However, the scope of all these studies was limited to hydrant flushing and no alternatives were introduced. Although hydrant flushing is the most effective way of WDS decontamination, it is not free from environmental problems. Whatever the technique of hydrant flushing, all the contaminated water is discharged to the environment and finally ends up in water bodies, agricultural fields, and/or wastewater treatment plants through combined sewers, which has a detrimental effect on the environment (Barbeau *et al.* 2005; EPA 2020).

To reduce the environmental impact, a containment pond located at the system periphery is evaluated here as an alternative solution. The pond will contain the contaminated water so that it does not spread to the environment with the impermeable liner obstructing infiltration so that the contamination does not reach the groundwater. The water can evaporate and leave behind the contaminant to be disposed of periodically. However, the pond location is critical, as its capacity will vary depending on its position in the distribution network.

The use of containment ponds is not an uncommon concept in the industrial sector. Ponds are constructed for various purposes, such as cooling, stabilization, settling, and oxidation. Cooling ponds are used to store and eventually cool down heated water from the nearby industries (Ryan *et al.* 1974; Mann & Mann Technology Limited Partnership 1991; Ramamoorthy *et al.* 2001; Barisevičiūtė *et al.* 2020). Stabilization ponds are used to remove or reduce turbidity, solid pollutants, and/or pathogens in many industries including wastewater treatment, mining, agriculture, aquaculture, etc. (Gray 1988; Sah *et al.* 2012). Settling ponds and oxidation ponds are also used for similar purposes (Elmaleh *et al.* 1996; Mispagel & Gray 2005; Merricks *et al.* 2007).

The purpose of this study was to evaluate the performance of a containment pond as a way of WDS decontamination for nine real WDSs. Here, the performance was evaluated based on the reduction of environmental impact caused during hydrant flushing alone. In addition, the best location of a containment pond based on minimizing cost and environmental contamination is examined. Capturing the contaminated water in a containment pond is more desirable than discharging to the storm sewer as the contaminant, e.g., salt, might not be removed by a conventional wastewater treatment plant and can even disrupt the biological processes used to remove pathogens. A single pond is modelled here for simplicity. The innovative aspects of this work are that it is the first such paper to address the use of using containment ponds for disposal of flushed contaminants from a WDS. No other paper has looked at that. Using containment ponds keeps the contaminant from interacting with the environment and thus polluting the environment.

Procedure

To capture the contaminated water in a containment pond as an alternative to hydrant flushing, and to find the best pond location, the contaminant transport of a conservative contaminant [in this study salt (Baird 2013) but the results will be applicable to any conservative contaminant] was modelled using the network solver EPANET (Rossman 2000), a network solver which can calculate pressure, velocity, discharge, and concentration of constituents of any WDS using a demand-driven analysis, provided that the user demands and characteristics of the WDS components are known. The proposed procedure is comprised of two phases in which the first phase is for determining the containment pond volume and the second phase is for determining the direct environmental impact, if any.

Phase I consisted of fresh water being pumped into the already fully contaminated system from the reservoir source and contaminated water discharged at the hydrant closest to the containment pond until the system was clean. If areas of the system were not cleared of contamination, then additional hydrants were opened near the contaminated area until the entire system was clean. A hydrant opening was simulated by discharging the highest hydrant flowrate that did not result in a negative pressure value anywhere in the system. Phase II consisted of measuring the volume discharged through the pond over the time to decontaminate the system. This determined the volume of excavation required for the pond. Then the amount of volume discharged from all the additional hydrants to clear the other areas of the system was added to calculate the total amount of water contaminating the environment, since it did not enter the pond.

Intuitively, it might seem that if the containment pond is placed at the furthest location from the reservoir, it should clear the system most efficiently since this is the way water has to travel through most regions of the system. To investigate the best pond location, possible pond locations examined here were at the three outer 'corners' of a system, away from the reservoir/s – where the second location was the furthest of all. While it is infeasible to model all possible pond locations, the 'corner' is representative of the main possible locations. In every case, all the valves at the consumers' ends were kept closed, like in unidirectional flushing or, in other words, there were no used demands (Antoun *et al.* 1999; Shah *et al.* 2001; Hasit *et al.* 2004; Walski *et al.* 2008; Wu 2015). Three simulations were run to determine the capacity of the containment pond at the selected locations. For each simulation, discharge was increased until either the pressure was zero at any time or location or any part of the system experienced a reduction in contamination level to zero. Pond volume was found by that value of discharge over the entire simulation period. In case/s where draining the system into a pond was not able to remove all the contaminant, fire hydrants at the dead ends were modelled as being open to clear the rest of the system. Opening fire hydrants do directly discharge the contaminated water to the environment, however this would have happened even more in conventional flushing procedures.

The optimal location of the containment pond for a system was determined by complete enumeration of the three 'corner' pond locations, with the objective of minimizing both cost and amount of contaminated water discharged into the environment. This was a multi-objective optimization problem in which cost was minimized due to typical budget constraints (Equation (1)) and the amount of contaminated water put into the environment was minimized (Equation (2)) since any contaminant is assumed to be detrimental (Barbeau *et al.* 2005):

Objective Function 1: Minimize Cost (1)

Objective Function 2: Minimize Environmental Impact (2)

subject to all pressure values being positive at all locations and times*.

*It is assumed here that any positive pressure is acceptable, although some references (Mays 2000) suggest a margin of safety of pressure = 20psi.

Pond total cost was comprised of the pond excavation and lining to prevent infiltration from the pond into the soil or groundwater aquifer, pumping energy costs, and alternative water source costs. Table 1 represents the unit cost per item

Table 1 | Unit cost per item for determining total cost

Item	Unit cost	Remark
Pond excavation	\$131.0/m^3 (\$3.7/ft^3)	This value was taken from Home Advisor (2019)
Pond lining	\$74.0/m^2 (\$6.9/ft^2)	This value was taken from Home Advisor (2019)
Pumping cost	Different for different systems in cost/day.	Unit pumping cost was obtained directly from EPANET output. This value was also different for different pond locations because of the change in energy used. Total pumping cost was determined by multiplying unit cost with time to clear the system from contamination.
Water bottles	\$0.54/0.5 L bottle	Number of water bottles required was determined assuming 55.6% of the total water demand to be domestic water demand (Shammas & Wang 2011). The unit cost per 0.5 L bottle was determined based on the average cost of 15 different suppliers

for pond total cost. Pond lining area was determined from the pond volume assuming a pond depth of 2.4 m (8 ft) based on USDA (2020), and both the pumping energy information and the number of water bottles required were obtained/determined from the EPANET output volume and the volume of water in a single water bottle. For provision of an alternative water source, it was assumed that only domestic water demand would be met during the flushing which is 55.6% of the total demand (Shammas & Wang 2011), and 0.5 L of bottled water would be supplied until decontamination was complete.

For comparison, the base case i.e., hydrant flushing was modelled using the same network solver EPANET (Rossman 2000). Though all the valves at the consumers' ends were kept closed as is done in unidirectional flushing (Antoun *et al.* 1999; Shah *et al.* 2001; Hasit *et al.* 2004; Walski *et al.* 2008; Wu 2015), no sequential order was maintained for opening the fire hydrants. Since the purpose of this study was to compare the environmental impact due to hydrant flushing and the use of containment pond, all the fire hydrants at the dead ends were modelled as simultaneously open.

Method application on real WDSs

In this study, nine looped real WDSs were used (Table 2) with systems ranging from 8 to 958 pipes, 6 to 874 junctions, 0 to 7 tanks, different tank positions as per Wang & Barkdoll (2017), 1 to 4 groundwater reservoirs, 0 to 3 surface-water reservoirs, and various range of water demand and pressure. All systems had diurnally fluctuating demand patterns and, in addition, pump controls that activated pumps at low tank water levels and deactivated pumps at high tank water levels. Most of the systems had residential water demand except System B and System C which had some industrial areas in addition to residential. All systems are based on real systems and no data were changed except the variable being studied here, containment ponds. The basis for choosing a pond location was the lowest cost and environmental impact.

Table 2 | Primary data of the water distribution systems

System	No. of pipes	No. of junctions	No. of tanks	Position of tank/s[a]	No. of GW reservoirs	No. of SW reservoirs	Type of the consumers	Range of average demand (LPS)	Pressure range (m)
A	8	6	1	FS	1	0	Residential	9.5–12.6	24–60
B	62	44	1	NS	1	0	Residential+Industrial	0.06–0.7	29–40
C	168	126	2	FS	1	0	Residential+Industrial	0.002–12.5	4–357
D	135	118	1	FS	1	0	Residential	0.06–3.2	14–107
E	394	347	2	FS/MS	1	0	Residential	0.001–1.4	16–276
F	958	874	1	ND	1	0	Residential	0.03–9.1	10–354
G	39	19	1	ND	1	0	Residential	12.6–63.1	19–50
H	551	504	0	-	4	3	Residential	0.02–3.05	10–144
I	429	388	7	FS/MS	1	0	Residential	0.0004–4.2	7–104

[a]Near-Direct (ND), Near-System (NS), Far-System (FS), Mid-System (MS) as per Wang & Barkdoll (2017). GW, groundwater; SW, saltwater.

RESULTS

It was found that adding a pond could successfully reduce the system contaminant concentration by storing contaminated water in the pond and not letting it enter the environment (Table 3, Figures S1–S9). In comparatively smaller and completely

Table 3 | Reduction of contaminated water to environment (%) after adding pond with hydrants opened to clear the remainder of the system

System	Pond Location #1	Pond Location #2	Pond Location #3
A	100	87	75
B	71	98	99
C	80	15	98
D	20	12	16
E	32	63	62
F	64	71	65
G	100	100	100
H	22	84	84
I	11	52	22

Table 4 | Volume of pond and time to clear the entire system with hydrants opened when needed

	Pond Volume (m^3)			Time to clear the system (hr)		
System	Pond Location #1	Pond Location #2	Pond Location #3	Pond Location #1	Pond Location #2	Pond Location #3
A	3,434	2,539	4,315	28	17	32
B	4,932	7,682	14,862	89	165	119
C	400,194	3,936	74,570	999	178	540
D	2,044	613	3,352	66	73	82
E	4,614	7,524	8,458	77	163	95
F	12,185	7,012	5,223	98	91	58
G	29,299	19,760	40,201	43	29	59
H	2,592	3,564	4,176	17	10	30
I	1,080	37,908	11,664	130	456	136

Table 5 | Pond total cost and environmental discharge for different pond locations

	Pond Total Cost[a] ($M)			Discharge to the Environment, V_{te} (M Liter)		
System	Pond Location 1	Pond Location 2	Pond Location 3	Pond Location 1	Pond Location 2	Pond Location 3
A	0.56	0.41	0.70	0.00	0.45	0.86
B	0.80	1.24	2.40	2.45	0.16	0.06
C	64.59	0.66	12.07	17.93	76.23	2.16
D	0.33	0.10	0.54	10.22	11.26	10.76
E	0.75	1.22	1.37	9.06	4.96	5.05
F	1.97	1.14	0.85	8.16	6.72	8.06
G	4.75	3.20	6.51	0.00	0.00	0.00
H	0.42	0.57	0.67	2.72	0.55	0.55
I	0.20	6.15	1.91	83.62	44.79	72.60

[a]Pond total cost includes pond construction cost, pumping cost, and bottled water cost as alternative water source.

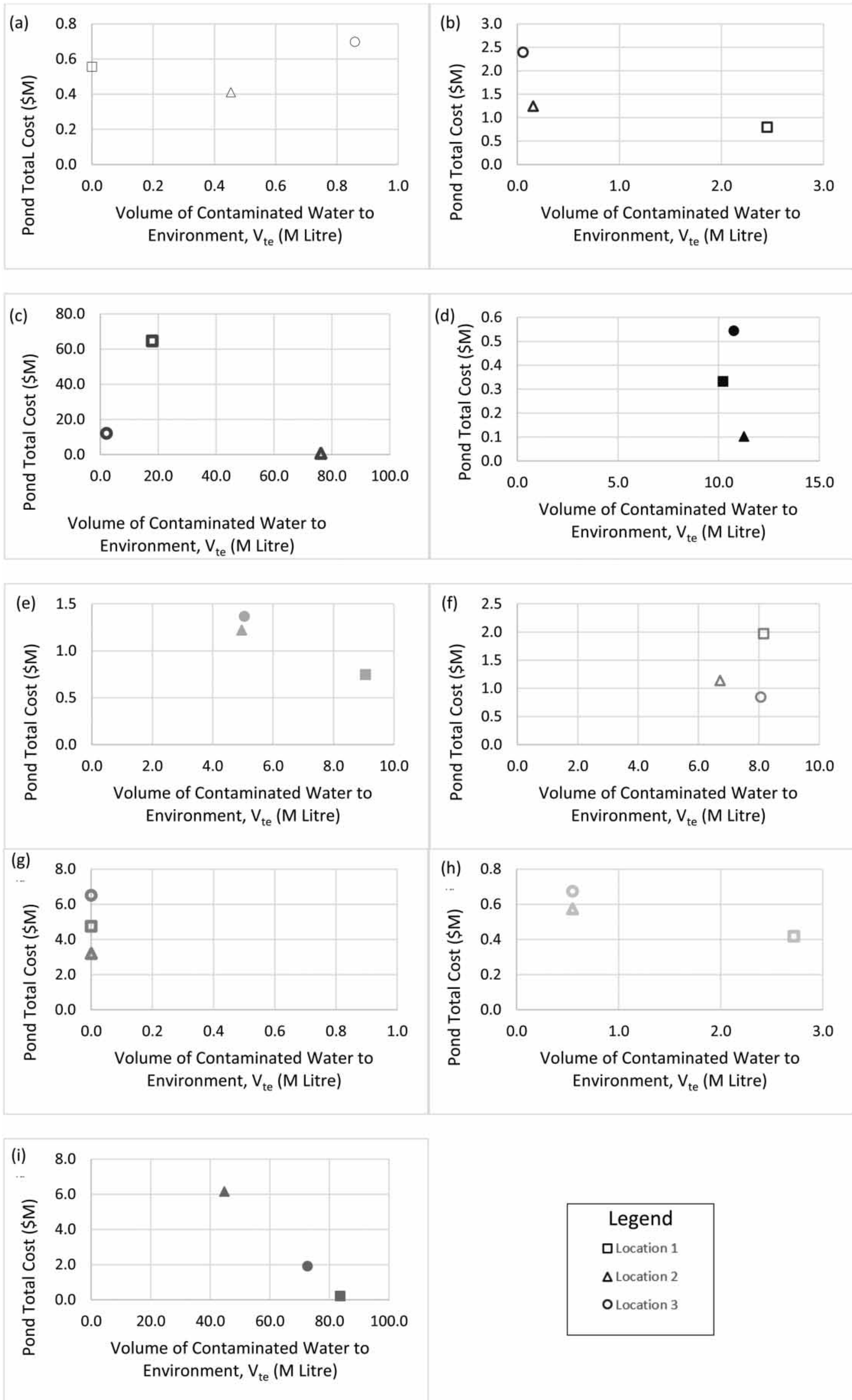

Figure 1 | Pond total cost vs volume of contaminated water to environment corresponding to (a) System A, (b) System B, (c) System C, (d) System D, (e) System E, (f) System F, (g) System G, (h) System H, and (i) System I.

looped System G, the reduction was 100% for all the pond locations. Two of the pond locations of Systems A, B, C, and H reduced the environmental impact by more than 80% and at least one or more pond location/s of Systems E, F, and I reduced the environmental impact by more than 50%. However, in System D the highest reduction percentage was significantly lower. Figures S1–S9 show the network condition of each system having ponds at their maximum capacities determined from Phase I. Here, the ponds' maximum capacities are the pond volumes represented in Table 4. The time to clear the system varied from system to system and is reflected in the volume of flow discharged. Using a pond cannot clear areas of the system away from the path from the source to the pond (See Figure S1 as an example). Table 4 presents the pond volume at each location for each system and the time required to clear the entire system with the help of hydrants, when needed. The pond volumes ranged from 613 m^3 (21,656 ft^3) (System D) to 400,194 m^3 (14,132,755 ft^3) (System C). Time to clear the systems ranged from 10 (System H) to 999 hours (System C). Table 5 shows the total cost required for constructing the pond at different locations along with the associated pumping costs and bottled water costs, and the concomitant volume of contaminated water discharge to the environment, V_{te}. Pond total costs ranged from $0.10 M (System D) to $64.59 M (System C). This cost will be termed 'pond total cost' hereafter.

To analyze the results, pond total cost vs V_{te} has been plotted for each system (Figure 1) and all the systems' plots have been combined for comparison (Figure 2). It was seen that the range of both the axes were different for different systems. Hence, all the outcomes were compared with the base case and normalized by dividing both the cost and V_{te} by the maximum value of

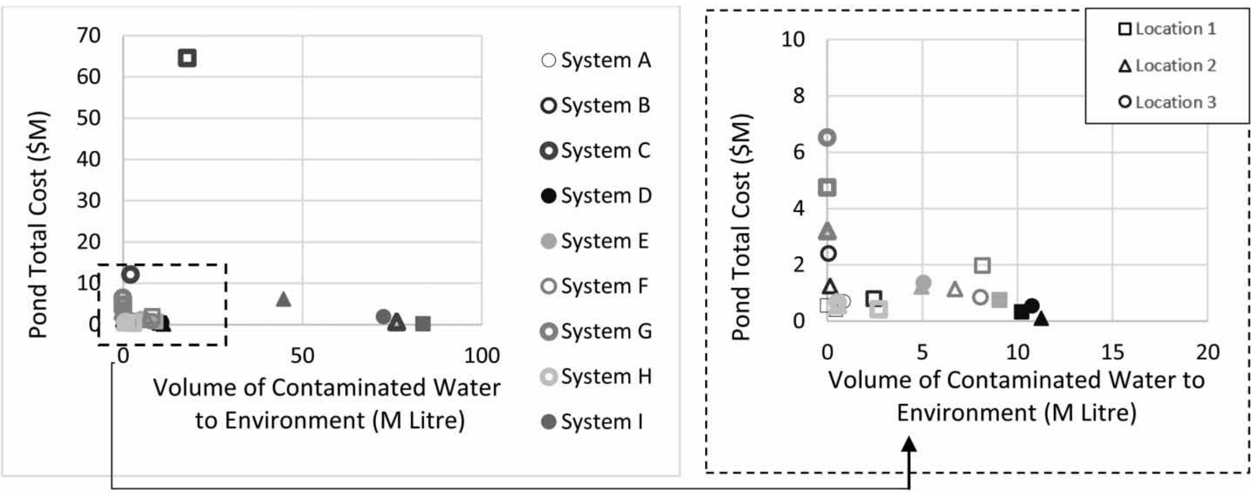

Figure 2 | Pond total cost vs volume of contaminated water to the environment for different pond locations showing that results are system dependent.

Table 6 | Associated cost and volume of contaminated water to environment during typical hydrant flushing

System	Cost ($K)	Volume of contaminated water to environment, V_{te} (M Liter)
A	1.77	3.43
B	1.58	8.46
C	48.56	90.07
D	3.03	12.74
E	3.77	13.34
F	9.42	22.95
G	8.65	16.70
H	0.22	3.47
I	30.74	93.44

Cost includes pumping cost and bottled water cost during hydrant flushing alone. V_{te} is the volume of contaminated water discharged to the environment from those hydrants.

the same series, thereby making the scale from zero to one. Here, the base case is typical hydrant flushing. The base case cost is the pumping cost and the water bottle costs during hydrant flushing alone and base case V_{te} is the volume of contaminated water discharged to the environment from those hydrants (Table 6). The base case cost ranged from \$0.22 K (System H) to \$48.56 K (System C) and the base case V_{te} ranged from 3.43 M Liter (System A) to 93.44 M Liter (System I). Both the normalized total costs and normalized V_{te} for different systems were plotted in the same graph (Figure 3). To compare the results with the base case, normalized total cost and V_{te} associated with the typical hydrant flushing were also plotted in the same graph. It is observed that some systems have a wide range of results e.g., Systems C, H, and I, while other systems have a narrow range e.g., Systems A, D, F, and G. However, Systems B and E have an intermediate range of results. Results having a wide range of values indicate that selecting a pond location has a tradeoff, in which some pond locations might be better from an economic point of view, while others will be better from an environmental perspective.

To choose the best location of the pond for each system from the analyzed locations, Figure 3 was utilized. From Figure 1, it is clear that a Pareto front exists for each system, which means contaminated water discharge to the environment cannot be reduced unless the pond total cost is increased. Hence, for each system, the pond location nearest to the origin in figure are optimal. Though the preliminary assumption was that Pond Location 2, being the furthest one from the reservoir, and, therefore, the location for which water would have to travel through the greatest portion of the system, would give the best result by clearing out more of the system, it was not always true. Pond Location 1 was the best solution for Systems B and E and Pond Location 3 was the best for Systems C, F, and I. This happened perhaps for the complex hydraulic characteristics of the systems. For the rest of the systems i.e., Systems A, D, G, and H, Pond Location 2 was preferable, as expected.

If a pond already exists on the system periphery, then it could be used and would avoid excavation and lining costs and thereby improve the feasibility of using ponds as a flushing option. Therefore, to examine all non-pond costs, normalized values of all costs i.e., pumping cost and bottled water cost vs normalized V_{te} have also been plotted for ponds at different locations and hydrant flushing alone to analyze the results based on other parameters (Figure 4). The best pond location based on non-pond costs was determined following the previous procedure i.e., for each system, the pond location nearest to the origin in Figure 4 was determined to be the best option. Results were negligibly different compared to total cost analysis (Figure 3) except for System D and System E. If pond construction cost is ignored and optimal pond location is selected based on non-pond costs and contaminated water to the environment, the best pond location for System D and System E were Pond Location 1 and Pond Location 3 instead of Location 2 and Location 1, respectively, when pond construction cost was considered.

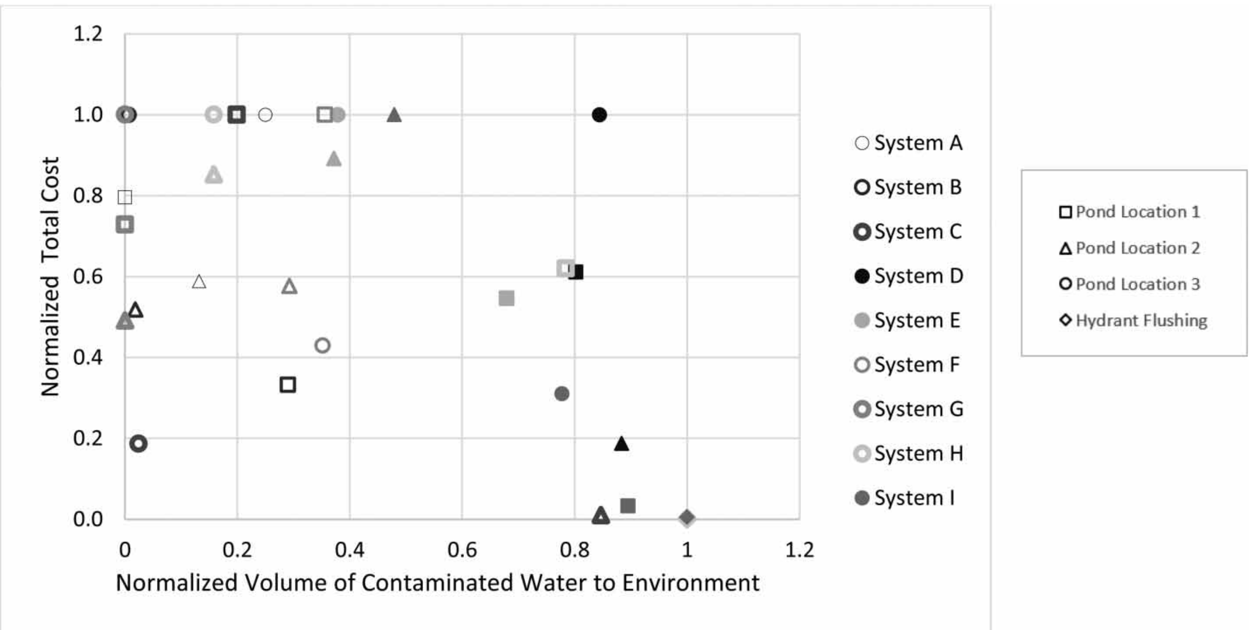

Figure 3 | Normalized pond total cost vs normalized volume of contaminated water to the environment for different pond locations showing that results are system dependent.

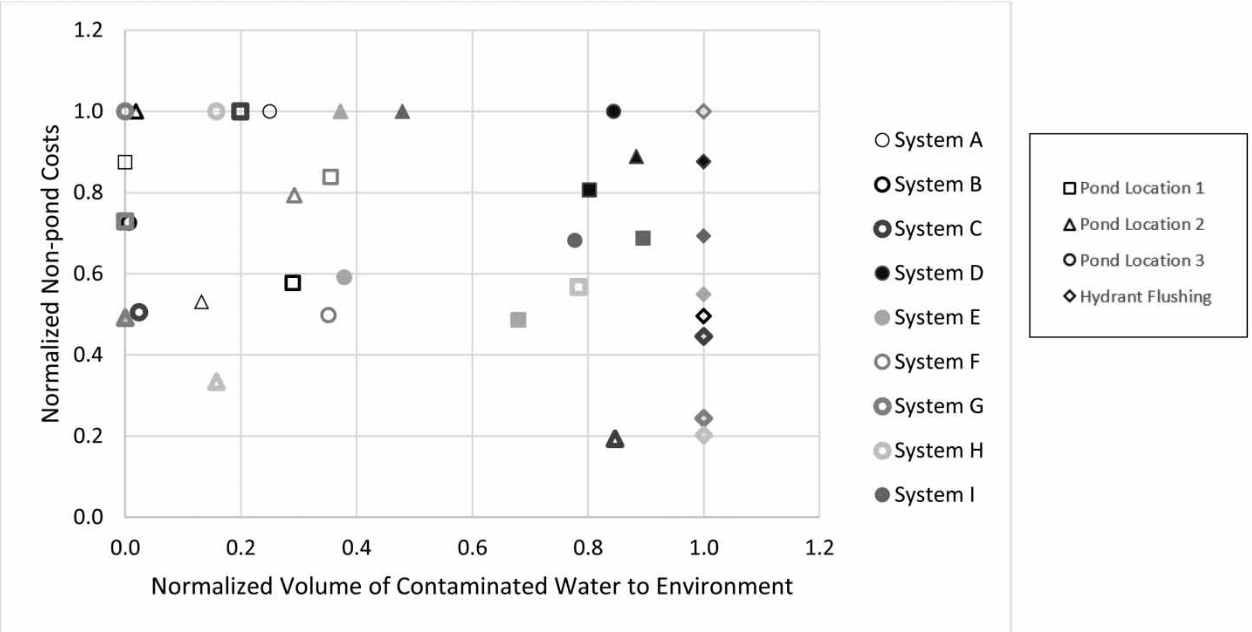

Figure 4 | Normalized non-pond costs vs normalized volume of contaminated water to environment for different pond locations showing that results are system dependent.

DISCUSSION

The purpose of this study was to explore an alternative to hydrant flushing for a contamination event. It was found that the containment pond method can work as an alternative. The major findings were that the method can reduce the environmental impact caused by hydrant flushing alone and optimal location of the containment pond is system dependent.

It is unclear if the results are generalizable since the pond feasibility is system dependent. The results could be somewhat more complete if all possible pond locations are studied, but the results may not change significantly, since the main pond locations were studied in this study. In addition, some cases call for large excavation amounts in the thousands of cubic meters and hundreds of hours for flushing. The feasibility of this must be decided by the water system managers.

Future improvement

In this study, optimal pond location was selected based on the pond total cost and the volume of the direct discharge of contaminated water. Here, pond total cost comprises the construction cost, pumping cost, and cost of buying water bottles. However, other parameters also exist e.g., production and transportation of the water bottles, production of the bottled water, type of harm caused to the environment from the contaminated water discharge, public perception of the decontamination procedures, peoples' willingness to spend for the land of the containment pond, etc. The inclusion of the above-mentioned parameters can be considered as future research. Using a pressure-driven analysis may have simplified the modeling, since the authors had to keep adjusting the outflow from the system into the pond until the pressure at the outflow junction was zero, which took some time.

CONCLUSIONS

The following points can be concluded from this study:

1. The proposed method for WDS flushing can be a better option than hydrant flushing since this method can successfully reduce environmental impacts due to hydrant flushing by up to 100%.
2. The method might not be able to reduce the environmental impact by 100% for areas away from the containment pond.
3. The best location of a containment pond is not always at the furthest location from the reservoir. So, before selecting the pond location all the outer corners of the system should be studied.

4. For some systems, containment pond location varies since a tradeoff exists in which some locations might be better from an economic point of view, while others will be better from an environmental perspective.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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