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SALT WATER INTRUSION IN WATER DISTRIBUTION SYSTEMS: ANALYSIS, SOLUTION, AND ECO-EFFICIENCY

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SALT WATER INTRUSION IN WATER DISTRIBUTION SYSTEMS: ANALYSIS, SOLUTION, AND ECO-EFFICIENCY

By

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Department of Civil, Environmental, and Geospatial Engineering

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Dedication

To my family and my advisor for their continuous support and encouragement.

Table of Contents

List of Figures

List of Tables

Author Contribution Statement

In this dissertation, I present the work I've done as the partial fulfillment of my doctorate degree at Michigan Technological University. Chapter 1 briefly describes the background and importance of my research, Chapter 2 is based on a manuscript submitted recently, Chapter 3 is based on a paper accepted in the Journal of Water Supply, Chapter 4 is based on a manuscript prepared for future submission, Chapter 5 reflects the major findings of the research and Chapter 6 refers possible extension of the research. Data collection, data analysis and interpretation, and manuscript preparation for Chapter 2 and Chapter 3 were done by the author with the help of Dr. Brian Barkdoll. Data collection, data analysis and interpretation for Chapter 4 were done by the author with the help of Dr. Robert Handler, and Dr. Brian Barkdoll assisted with the manuscript preparation. I sincerely thank my co-authors for their contributions.

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I would like to thank my advisor Dr. Brian Barkdoll for his continuous support and direction to complete my research. I also appreciate his friendly and optimistic behavior and expert mentorship which always made me feel at home and helped me to stay focused.

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List of Abbreviations

DALY	Disability-Adjusted Life Years
GHG	Greenhouse Gas
GIS	Geographic Information System
HDPE	High Density Polyethylene
LCA	Life Cycle Assessment
MJ	Megajoules
PDF-m^2-y	Potentially Disappeared Fraction of contaminant species per m^2 per year
PET	Polyethylene Terephthalate
WDS	Water Distribution System

Abstract

Since many water distribution systems (WDSs) experience saltwater intrusion, system behavior during saltwater intrusion is important. An alternative to the currently accepted WDS decontamination method of hydrant flushing is needed since during the current procedure all contaminated water is discharged to the surroundings which imposes environmental impacts. Hence, this research was conducted to study salt spread in different WDSs and to seek an alternative to hydrant flushing as a way of WDS decontamination.

First, salt contamination was modelled in real water system models to document the salt spread. It was found that (1) if salt enters as a short pulse, it may contaminate different parts at different times; (2) in a multi-reservoir system if any reservoir remains fresh during a salt contamination event, contamination might take a longer time to reach the system edges; and (3) for all system types, time to clear the system from salt contamination is linearly correlated to the rate of salt entry at the source.

Second, the performance of a containment pond was evaluated as an alternative to hydrant flushing, in which a pond lined with impermeable material will be constructed in a suitable place. Network modeling was performed, and it was found that (1) a containment pond can be a better option for WDS decontamination from an environmental viewpoint; (2) flushing only into the containment pond cannot clear all areas of the system; and (3) for some systems, some pond locations might be better from an economic perspective, while other locations will be better environmentally.

A containment pond also has some environmental impact since the pond requires initial construction. Also, the decontamination time depends on the decontamination option chosen. Finally, a life cycle assessment study was performed using SimaPro for both the decontamination options and the impacts were assessed using IMPACT 2002+. The results show that (1) a containment pond can reduce the environmental impact caused during hydrant flushing alone; (2) using a containment pond can be more effective in an urban area; and (3) the time needed for the decontamination and the area exposed to contaminated water significantly affect environmental impact.

1 Introduction

1.1 Background

Water distribution systems (WDSs) are designed to provide safe, uninterrupted, and sufficient drinking water to the consumers (Viessman and Hammer 1998, Mays 2000, Encyclopedia Britannica 2018). A WDS can be branched or looped, and it may have pumps directly connected to the storage tank or pumps connected into the system. Some systems do not need pumps since the water flows by gravity. The pumps' on/off status depends on the tank level, which varies following the varying consumer demand at different times of the day. A WDS can be supplied either from a single or multiple water source, where the sources can either be ground water, surface water, or both. For controlling water flow, valves are placed at different parts of a system, and hydrants are placed for emergency situations (Viessman and Hammer 1998, Mays 2000, Wu 2015).

Though the main purpose of a WDS is to provide safe and uninterrupted drinking water (Viessman and Hammer 1998, Mays 2000, Rasek and Brumbelow 2013), contamination intrusion is not an uncommon incident (Hrudey and Hrudey 2004, Craun et al. 2006, Hrudey and Hrudey 2007, Seth et al. 2016) along with many other water issues including corrosion, microbiology, taste and odor concerns etc. (AWWA 2017). Water quality in any system can deteriorate due to the presence of a contaminant. Any WDS can get contaminated both by intentionally injected chemicals or by an unintentional introduction of contaminants from the surface or ground water (Seth et al. 2016). Contamination can also take place due to physical deterioration of the WDS components or equipment (Rasek and Brumbelow 2013).

Contaminant intrusion into WDSs has been studied experimentally (Jones et al. 2019), through modeling (Yang et al. 2016; Mansour-Rezaei et al. 2013), using data mining (Shen and McBean 2013; Oliveira et al. 2018) and GIS (Vairavamoorthy et al. 2004). In addition to salt water intrusion into the water source from groundwater pumping, overland flow, or sea-level rise, any opening or crack in the joint or pipe can allow contaminant intrusion (Shao et al. 2020; Collins et al. 2011). The intrusion rate can also be affected by the properties of the surrounding porous media (Yang et al. 2014). In any contamination incident, quick detection, rapid response, and mitigation can improve public health (Poulin et al. 2010; Seth et al. 2016; Zafari et al. 2017). Research studies have been conducted on inline sensors for contamination detection (Ohar et al. 2015; Palleti et al. 2016; de Winter et al. 2019; Sankary and Ostfeld 2019; Giudicianni et al. 2020) and real-time response (Lifshitz and Ostfeld 2019) to any contamination incident; however, some uncertainty still exists due to the lack of reliable data and complex nature of environmental systems (Mansour-Rezaei et al. 2011).

Apart from accidental or intentional WDS contamination, saltwater intrusion is another important incident, mostly occurring in coastal areas due to over-extraction of water from fresh-water aquifers (Edwards et al. 2009, Gleeson et al. 2012, Doell et al. 2014, Spellman 2017). Many coastal areas including Los Angeles (Edwards 2002, Spellman 2017), Georgia (Spatafora 2008), northeastern Florida and south Florida (Spechler 2001, Czajkowski et al. 2018), southwestern Nigeria (Ayolabi et al. 2013, Yusuf and Abiye 2019), Tamilnadu of India (Gopinath et al. 2016), and coastal areas of Bangladesh (Faneca Sànchez et al. 2015, National University of Singapore 2020) consider saltwater intrusion as a significant threat to their drinking water quality. The presence of salt in surface water is also not uncommon in the regions that experience snow and ice, since road deicing salt is used in those regions to reduce road accidents during winter (Carmody 2016, Hintz et al. 2021). When the groundwater aquifer and/or surface water becomes contaminated by saltwater, then the salt can enter the water treatment plant and subsequently the WDS, since generally salt is not removed in the water treatment process.

The most common way of salt monitoring is by collecting the sample and by analyzing them in the laboratory. Unfortunately, this method is expensive, time consuming and labor-intensive (Benjankar and Kafle 2021). Some researchers are working on developing automated real-time salt concentration measuring sensors. However, they need further study to overcome the calibration error and error due to variation in environmental conditions (Lambrou et al. 2014, Abuowda et al. 2017, Benjankar and Kafle 2021, Rana and Kapadia 2021).

When treatment is not convenient in a contamination incident, flushing using fire hydrants is a common way of WDS decontamination (Khanal et al. 2006; Friedman 2002; Seth et al. 2016; Shafiee and Berglund 2017). Generally, hydrant flushing is performed using two techniques – conventional and unidirectional. In conventional flushing, fire hydrants are opened (usually one by one) sequentially or non-sequentially without changing any valves. In contrast, in unidirectional flushing, fire hydrants are opened sequentially, while the pressure valves located near the consumers buildings are kept closed. Conventional flushing can fail to decontaminate a system entirely due to the lack of sufficient velocity within the pipes. In contrast, unidirectional flushing can ensure adequate velocity, which is 0.8 m/s (2.5 ft/s) to 3 m/s (10 ft/s). The velocity is selected based on the type of the contaminant (since different contaminant have different resistance) and the size of the system (Antoun et al. 1999, Shah et al. 2001, Hasit et al. 2004, Walski et al. 2008, Martin and Ries 2014, Wu 2015, Xie et al. 2015). Compared to conventional flushing, unidirectional flushing can reduce water usage by up to 40%; however, unidirectional flushing also involves some constraints, including time allocation, proper management, and labor. Another available flushing technique is continuous blow-off, mostly for stagnant areas of a WDS including dead ends and large pipes. However, this technique is not reliable, in general, because of the insufficient velocity obtained within the pipes (Oberoi 1994, Antoun et al. 1999, Hasit et al. 2004, Barbeau et al. 2005, Rebolledo et al. 2020). Some WDSs follow a routine flushing program to maintain the water quality where the frequency can be monthly to annually. The frequency is generally selected based on the size of the system and the system’s susceptibility to any chemicals, high level of disinfectant residual, sediment accumulation, corrosion, and/or customer complaints (Friedman et al. 2002, MELCC 2019).

During typical hydrant flushing, all the contaminated water is discharged to the surroundings of the fire hydrants. Thus, the contaminated water can end up anywhere, including roads, agricultural lands, water bodies, lawns, wastewater treatment plants, etc., which can have some adverse effects on the environment. In contrast, flushing into a pond lined with an impermeable material can eliminate this environmental impact by containing the contaminated water (Sheefa and Barkdoll 2020; Sheefa et al. 2021). However, such a pond is also not free from environmental impact. Again, the pumping energy requirement and the time to decontaminate the system will be different for hydrant flushing and the use of a containment pond which also raises the question of the best WDS decontamination option from an environmental viewpoint.

1.2 Network Modeling Software EPANET

EPANET (Rossman 2000) is a water distribution network solver that can calculate the discharge, pressure, and chemical concentration at all points throughout a distribution system given the pipe, junction, pump, reservoir, tank, and user information. Pipe information includes the length, diameter, and roughness of the pipe, junction information includes the elevation of the junction and the user water demand, pump information includes the pump head versus flow relationship, reservoir information includes the head of the water source and water quality parameter (if any), and tank information includes tank diameter, minimum and maximum water levels in tank, mixing model and water quality parameter (if any). User water demand can be residential or industrial and it can be different at different parts of a system depending on the neighborhood. In addition, a single neighborhood can have multiple demand categories. Residential demands at the junctions generally vary in a periodic way over the course of a day (an example is shown in Figure 1-1), in contrast, industrial demands can be for only limited duration (e.g., Figure 1-2).

EPANET use advection mechanism to trace contaminant at any part of the system. Advection refers to the bulk movement of the contaminant carried by the flowing water. In real life, a contaminant can also be transported by dispersion or diffusion. Dispersion refers to the movement of the contaminant from higher concentrated area to lower concentrated area and diffusion refers to the contaminant movement due to molecular motion.

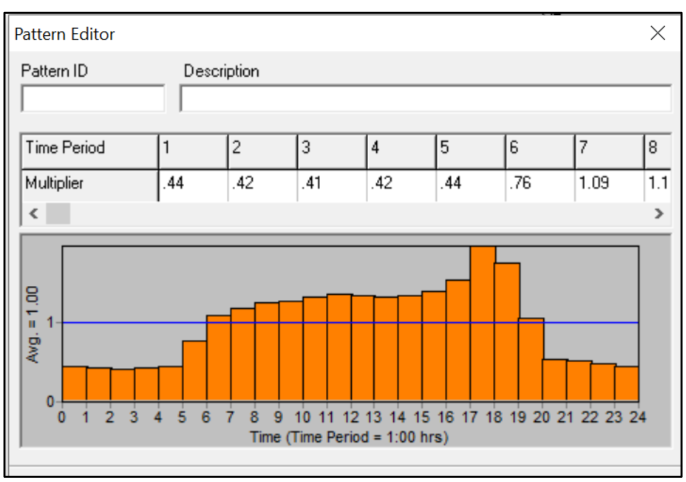

Figure 1-1. An example of residential water demand pattern in pattern editor of EPANET.

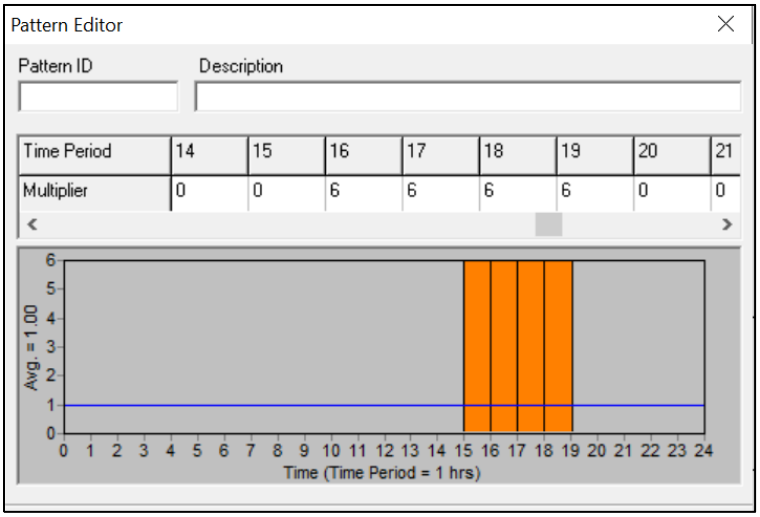

Figure 1-2. An example of industrial water demand pattern in pattern editor of EPANET.

1.3 Research Objectives

There are published/ongoing studies on how salt enters a ground water aquifer, and how this salt intrusion can be prevented or mitigated. However, there is no research incorporating the fate of salt in distribution systems. Again, many studies are available for hydrant flushing, including the efficacy of hydrant flushing (Van Bel et al. 2019), identifying factors (e.g., weather challenge including severe storm and snow accumulation) contributing to hydrant damages using GIS (Makar 2016), optimization of hydrant opening during a hydrant flushing procedure (Poulin et al. 2010, Deuerlein et al. 2014), and the performance of hydrant flushing rules based on consumer reactions (Shafiee and Berglund 2017). However, prior to this dissertation research, no studies were available on a containment pond as an alternative to hydrant flushing.

The overall goal of this research is to study salt contaminant in different WDSs and to seek an alternative to hydrant flushing as a way of WDS decontamination. This overall goal is achieved through the accomplishment of the following objectives:

1. Simulating salt spread in different WDSs (Chapter 2),
2. Evaluating the performance of a containment pond as an alternative to hydrant flushing (Chapter 3), and
3. Studying comparative life-cycle assessment of WDS decontamination using hydrant flushing and a containment pond (Chapter 4).

2 Spread of Salt through Municipal Water Distribution Systems

One journal paper derived from this chapter has been published in "Environment, Development and Sustainability" Journal.

[Sheefa, D.E., and Barkdoll, B.D., 2022. "Spread of salt through municipal water distribution systems." *Environment, Development and Sustainability,* pp.1-21.]

2.1 Introduction

Saltwater can enter a system in multiple ways. One is through intrusion into groundwater. Also, salt may enter in certain locations, and perhaps in pulses, through surface water infiltration into the groundwater aquifer. Coastal cities that obtain water from the groundwater aquifers can encounter saltwater intrusion. This intrusion occurs when salt is drawn from the ocean into the freshwater aquifer because of excessive freshwater withdrawals and/or sea-level rise (Xiao et al. 2019, Roy and Datta 2018, Tran Anh et al. 2018). If the groundwater aquifer is contaminated by salt, the contamination can enter the water treatment plant and eventually the water distribution system. Few solutions exist for driving the saltwater back to the ocean. One solution is freshwater injections into the aquifer forcing the saltwater back towards the ocean. This requires large amounts of freshwater and concomitant pumping costs. This may not always achieve the desired results (Spatafora 2008, Edwards 2002).

Multiple sources of surface water salt exist including road salt, water treatment chemicals, sewage effluent, domestic water softeners, etc. An increase in the salt level in distribution systems is not uncommon in the areas where road salt is used as a deicing agent (Kelly et al. 2018, Pieper et al. 2018). The City of Flint, Michigan is a prime example of surface water salt contamination from road salt, among other things, that made the distribution system corrosive and exposed lead in pipes, thereby introducing lead into the drinking water, leading to multiple cases of lead poisoning (Carmody 2016). Treatment options exist but are costly (Chawaga 2017).

The fact that there are systems experiencing saltwater intrusion, and this is expected to be an increasing issue in the future due to sea-level rise, makes this an important present and emerging issue worthy of study. Conservative contaminants, such as salt, have been studied for single systems (Sheefa and Barkdoll 2020), as well as other issues such as pumping costs (Mala-Jetmarova et al. 2015), contaminant source identification (Yang and Boccelli 2014), use of field data in modeling (Dawsey 2006), and contaminant intrusions (Nilsson et al. 2005). Each of these studies, however, deals with a single system.

If a system is contaminated by salt, then an effort to use modeling to guide understanding of the spread of salt is needed. Therefore, the objective of this study is to be the first to model salt as a contaminant in various distinct and real water systems to document the systems' behavior in events of instantaneous, short-duration pulse, and gradual intrusion of saltwater, with implications for aiding system managers.

2.2 Procedure

Computer modeling was performed using the network solver EPANET (Rossman 2000). Thirteen real water distribution system models were used (Table 2-1), with systems ranging from 8 to 14,824 pipes, 6 to 12,525 junctions, 0 to 4 tanks, different tank positions as per Wang and Barkdoll (2017), 1 to 4 groundwater reservoirs, 0 to 3 surface water reservoirs, and both branched and looped configurations. The studied systems had tank/s at Near-Direct (ND) position, Near-System (NS) position, Far-System (FS) position or Mid-System (MS) position (Wang and Barkdoll 2017), where ND implies that the tank is directly connected to the water source via pumping station, NS implies the tank is near to the water source but not directly connected to the pumping station, FS implies that the tank is far away from the water source and at the other end of the system, and MS implies that the tank is situated at the middle of the system. For all the systems, the tank mixing method was "mixed" which incorporates complete mixing (Rossman 2000). Equilibrium conditions of the systems were ensured before modeling the contamination. Equilibrium occurred after running the simulation until the pump discharge rate exhibited a repeating diurnal pattern. Existing pressure values were all acceptable and changing contaminant levels did not change pressure. Eight systems had the same demand pattern at all junctions and, therefore, all junctions experienced the maximum and minimum discharge values simultaneously throughout the systems. The rest of the systems had multiple and/or isolated demand patterns representing the intermittent water demand at different parts of the system.

Depending on the type of the source, the type of salt in any salt-contaminated water distribution system can be different. For example, 90% of the salinity of seawater comes from sodium chloride (USGS 2016). On the other hand, several road deicing salts are available including sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), etc. (Hintz and Relyea 2019). Sodium chloride was chosen as the type of salt contamination modeled since it is the major component of seawater and the most common type of road salt (Kelly et al. 2018, Hintz and Relyea 2019).

The maximum level of salt concentration possible is 35,000 mg/L, since this is the concentration in seawater (USGS 2016). However, a source would likely be taken out of service long before the salt level in the water reached this level. On the other hand, studying any other concentration value will not be representative of all scenarios since whether the source is sea-salt or road-salt, the concentration level will be different in different cases. So, for the purpose of generalization, the salt percentage was documented throughout the study.

Salt intrusion can be continuous if the ground water aquifer is affected by sea salt. Salt intrusion can also take place as a pulse since this event can result from a large storm (Williams 2010), or it can take place during the winter seasons when the road-salts are in use (Hintz and Relyea 2019). To represent both types of scenarios, instantaneous and gradual salt intrusion for different durations at the reservoir were modeled. A sudden and continuous salt intrusion was modeled for instantaneous salt intrusion event to represent the worst-case scenario. In contrast, a wide range of salt intrusion durations was considered for gradual salt intrusion beginning with 2 hrs. (S-1) and extending to 2 years (S-12), to characterize shorter durations as a pulse and the longer durations as a gradual continuous intrusion (Table 2-2). In each case, the maximum concentration value was kept constant for ease of comparability.

Table 2-1. Primary data of the water distribution systems.

System	No. of Pipes	No. of Junctions	No. of tanks	Tank Position*	No. of GW Reservoirs	No. of SW Reservoirs	Demand Pattern	Type of Connection
1	115	115	1	ND	1	0	4-discontinuous	Branched
2	24	24	1	NS	1	0	1-mostly continuous	Branched
3	14	14	1	FS	1	0	3-discontinuous	Branched
4	8	6	1	FS	1	0	1-continuous	Looped
5	62	44	1	NS	1	0	1-continuous, 1-discontinuous	Looped
6	168	126	2	FS	1	0	1-continuous, 1-discontinuous	Looped
7	135	118	1	FS	1		1-continuous	Looped
8	394	347	2	FS & MS	1	0	1-mostly continuous	Looped
9	958	874	1	ND	1	0	1-continuous	Looped
10	14,824	12,525	4	ND & MS	2	0	2-continuous	Looped
11	39	19	1	ND	1	0	1-continuous	Looped
12	41	41	1	MS	1	0	1-mostly continuous	Branched
13	551	504	0	-	4	3	1-continuous	Looped

*Near-Direct (ND), Near-System (NS), Far-System (FS), Mid-System (MS) as per Wang and Barkdoll (2017)

Table 2-2. Salt intrusion scenarios for the event of gradual salt intrusion.

Scenario	**Duration of Salt Intrusion at the Reservoir**	**Time to Reach Maximum Salt Level at the Reservoir**
S-1	2 hrs.	1 hr.
S-2	4 hrs.	2 hrs.
S-3	1 day (24 hrs.)	12 hrs.
S-4	2 days (48 hrs.)	1 day (24 hrs.)
S-5	6 days (144 hrs.)	3 days (72 hrs.)
S-6	2 weeks (336 hrs.)	1 week (168 hrs.)
S-7	4 weeks (672 hrs.)	2 weeks (336 hrs.)
S-8	2 months (1,440 hrs.)	1 month (720 hrs.)
S-9	4 months (2,880 hrs.)	2 months (1,440 hrs.)
S-10	8 months (5,760 hrs.)	4 months (2,880 hrs.)
S-11	16 months (11,520 hrs.)	8 months (5,760 hrs.)
S-12	2 years (17,280 hrs.)	1 year (8,640 hrs.)

The instantaneous salt intrusion was modeled for all 13 systems. However, for the gradual salt intrusion event, only four systems (Systems 3, 8, 9, and 13) were selected for the ease of documentation. Systems were selected in such a way that they represent different sizes, different tank positions, different types of reservoirs, different types of demand patterns, and different types of connection.

To analyze an instantaneous salt intrusion event, a continuous salt concentration of 100% was instantaneously added at the source reservoir(s), which started with no salt, as did the entire system, including the storage tanks. In contrast, when saltwater intrudes into a freshwater aquifer in a gradual fashion, it most likely contaminates the aquifer linearly with time (Heiss and Michael 2014). Hence, to analyze gradual salt intrusion, 12 salt intrusion rates were added at the reservoir(s), which started with no salt, as did the entire system, including the storage tanks. In each case, the rate of saltwater intrusion was linear, reaching the maximum amount i.e., 100% linearly at the reservoir/s over periods of in 1 hr. to 12 months for the studied scenarios (Table 2-2). After reaching the maximum level, the concentration of the salt was modeled to linearly come back to zero (Figure 2-1). The rate of change i.e., the increase and the subsequent decrease of salt concentration over time was assumed to be the same. All these assumptions were made based on the information from Heiss and Michael (2014) and for modeling convenience.

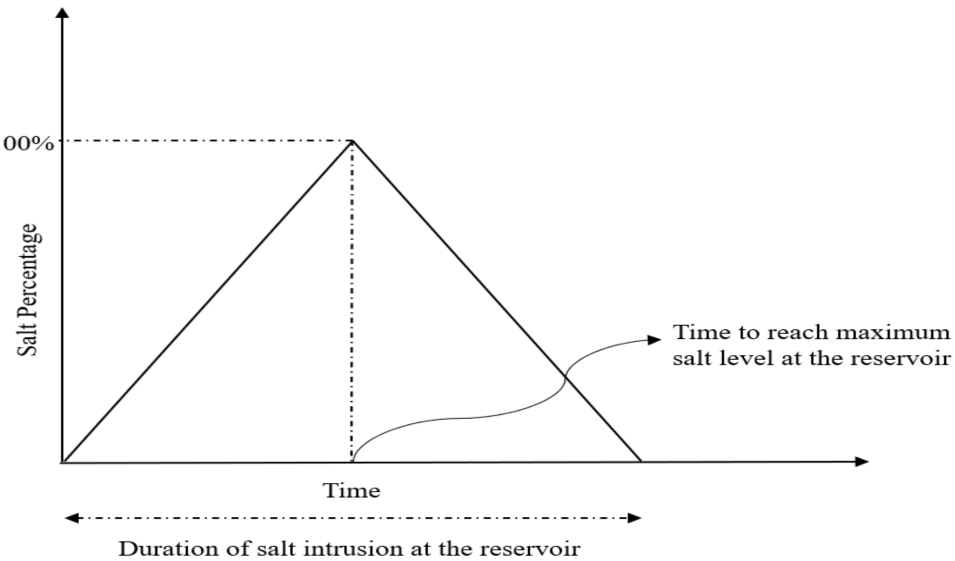

Figure 2-1. Salt percentage input over time following the same rate of change for the gradual salt intrusion event.

It was assumed that there is no decay of the salt concentration (Baird 2013) i.e., the results apply for any conservative contaminant. For the instantaneous salt intrusion event, simulations were run for a sufficient time for all system junctions to be contaminated with salt. For the gradual salt intrusion event, simulations were run for a sufficient time for all system junctions to be contaminated with salt and subsequent termination of contamination. A junction was assumed to exhibit a trace amount of salt when the concentration corresponded to a negligible concentration of 0.1% of the original concentration of salt.

For System 13, which is a multiple-reservoir system (Table 2-1), it was primarily assumed that the salt concentration was equal in all the reservoirs, including the surface water reservoirs at the event of gradual salt intrusion. It is possible that different reservoirs get contaminated at different rates. Some reservoirs can even stay fresh, thereby resulting in numerous contamination scenarios. Another set of simulations was run for System 13 to compare cases when some reservoirs were contaminated, and others remained clean at the event of gradual salt intrusion.

Since water distribution systems are complex and different parts of the systems behave differently due to various pipe sizes and demands, it is difficult to show the entire system behavior for the entire extended period analysis. A contour plot was developed for each of the systems at instantaneous salt intrusion event, and two types of junctions were selected to demonstrate the systems' behavior for the analyzed scenarios with gradual salt intrusion events– 'Beginning Junction' and 'End Junction'. The junction which had some water demand and was geographically nearer to the reservoir, was selected as the 'Beginning Junction'. Similarly, the junction which had some water demand and received contamination later than any other junction was selected as the 'End Junction'. Since System 13 has multiple reservoirs, there were multiple Beginning Junctions.

2.3 Results

2.3.1 Analysis of Instantaneous Salt Intrusion

Figure 2-2 to Figure 2-14 show the hour of salt intrusion contour of Systems 1 through 13 showing the salt arrival times for several junctions in the event of instantaneous salt intrusion. These contour plots also show the velocity at each pipe for the highest demand hour and, therefore, the highest velocity times, since convection by velocity is the dominant transport mechanism.

System 1 is a branched WDS consisting of 115 pipes, 115 junctions, 1 ground water reservoir, and 1 tank directly connected to the pump station. The system has four isolated demand patterns. It was seen that for the instantaneous salt intrusion event, salt enters the central section of the system later since the tank fills up first and then from there to the main system (Figure 2-2). It was also observed that a junction close to the source can be the last to be contaminated due to limited duration demands. However, the time for salt to reach such junctions could be faster if EPANET could have modelled diffusion transport mode in addition to advection. In this long and narrow system, salt reached most neighboring junctions as the salt is transported along the mainline.

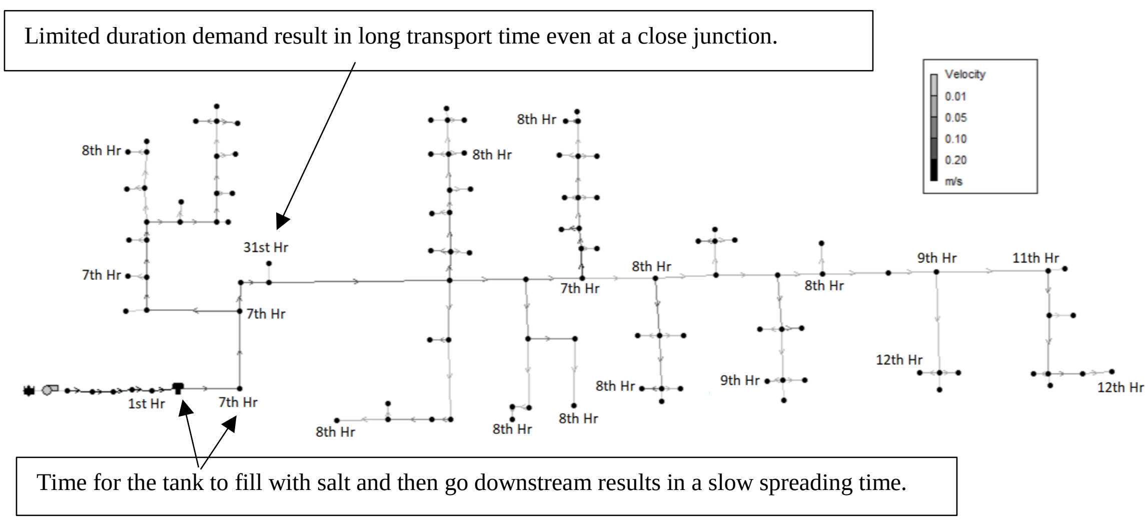

Figure 2-2. Hour of salt intrusion contour of System 1 for instantaneous salt intrusion event.

System 2 is another branched distribution system consisting of 24 pipes connected by 24 junctions, one storage tank situated near the source which is a groundwater reservoir, and a single demand pattern that is mostly continuous except for some hours at night. It was seen that salt reached the junctions in sequential geographical order following the instantaneous salt intrusion event (Figure 2-3). However, a junction close to the reservoir was contaminated last due to low demand.

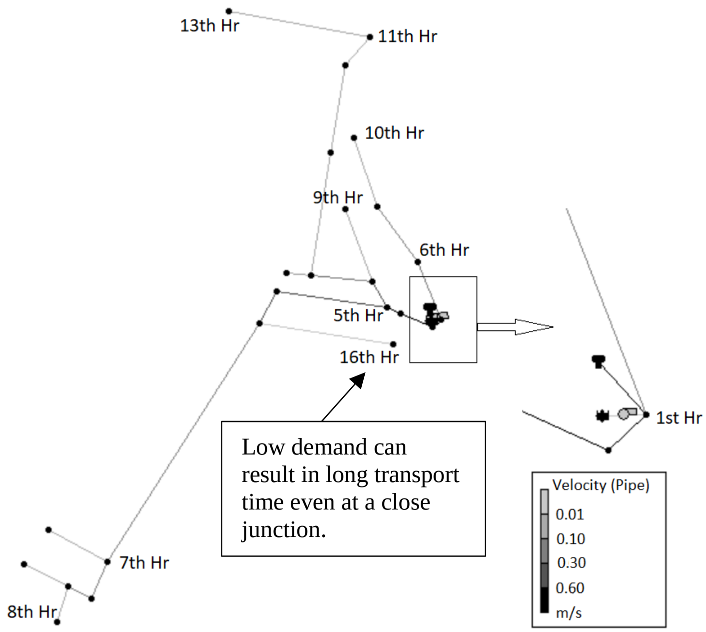

Figure 2-3. Hour of salt intrusion contour of System 2 for the instantaneous salt intrusion event.

System 3 is another branched WDS with 14 pipes connected by 14 junctions. This system gets water from a ground water reservoir, but the tank is located far from the reservoir. Though this system is comparatively small in terms of junctions and pipes, there are three discontinuous demand patterns (Table 2-1). It can be seen from Figure 2-4 that salt spreads more quickly through the system following the instantaneous salt intrusion event, since the tank is at the far end and not in the mainline, and also that salt reaches some junctions late due to low demand and a long distance.

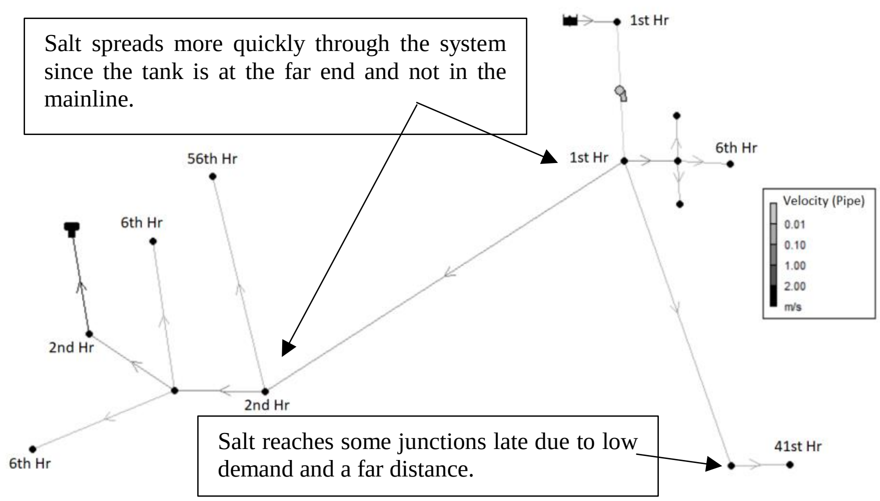

Figure 2-4. Hour of salt intrusion contour of System 3 for the instantaneous salt intrusion event.

System 4 is a very small, looped water system having only 8 pipes, 6 junctions, one tank situated far away from the single ground water reservoir, and one consistent demand pattern. For the instantaneous salt intrusion event, salt reached the junctions in sequential geographical order in this system like System 2 (Figure 2-5).

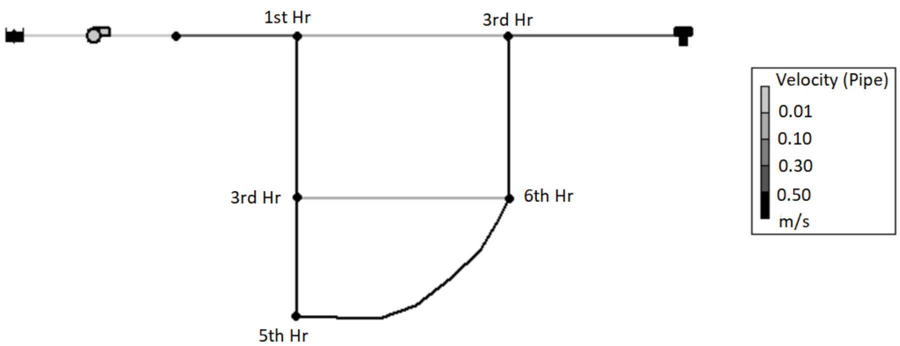

Figure 2-5. Hour of salt intrusion contour of System 4 for the instantaneous salt intrusion event.

System 5 is a looped WDS consisting of 62 pipes, 44 junctions, one tank situated near the system, and two different demand patterns. This system is supplied from a single groundwater reservoir. The mainline is contaminated immediately in the instantaneous salt intrusion event; however, salt reached the other parts eventually (Figure 2-6). Limited duration demand resulted in long transport time even at a junction close to the reservoir.

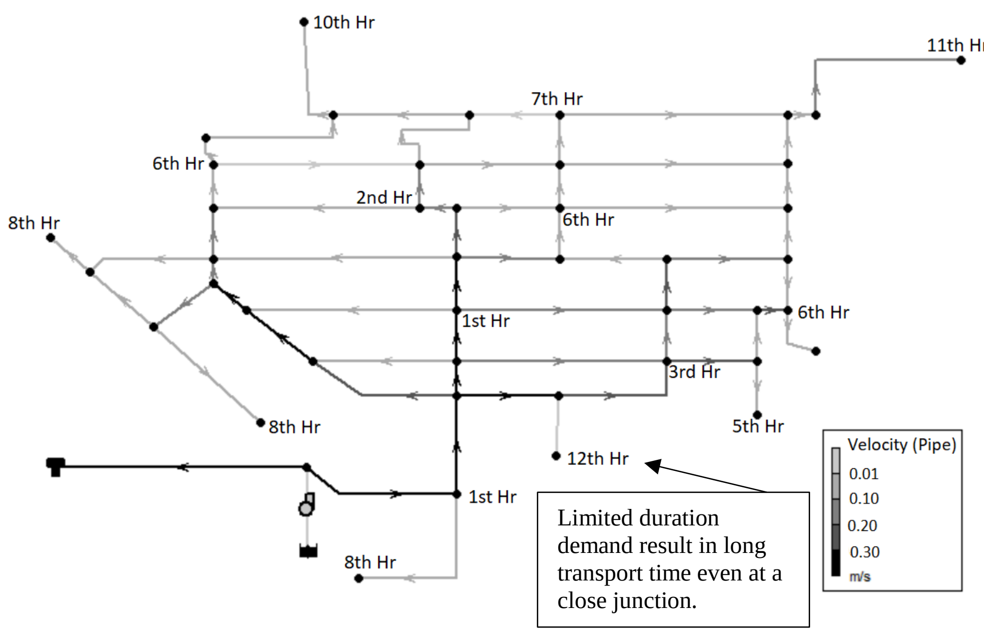

Figure 2-6. Hour of salt intrusion contour of System 5 for the instantaneous salt intrusion event.

System 6 is another looped distribution system consisting of 168 pipes connected by 126 junctions, two tanks both situated far away from the reservoir, one groundwater reservoir, and two different demand patterns. The neighboring parts were contaminated as the salt was transported through the mainline following the instantaneous salt intrusion event (Figure 2-7).

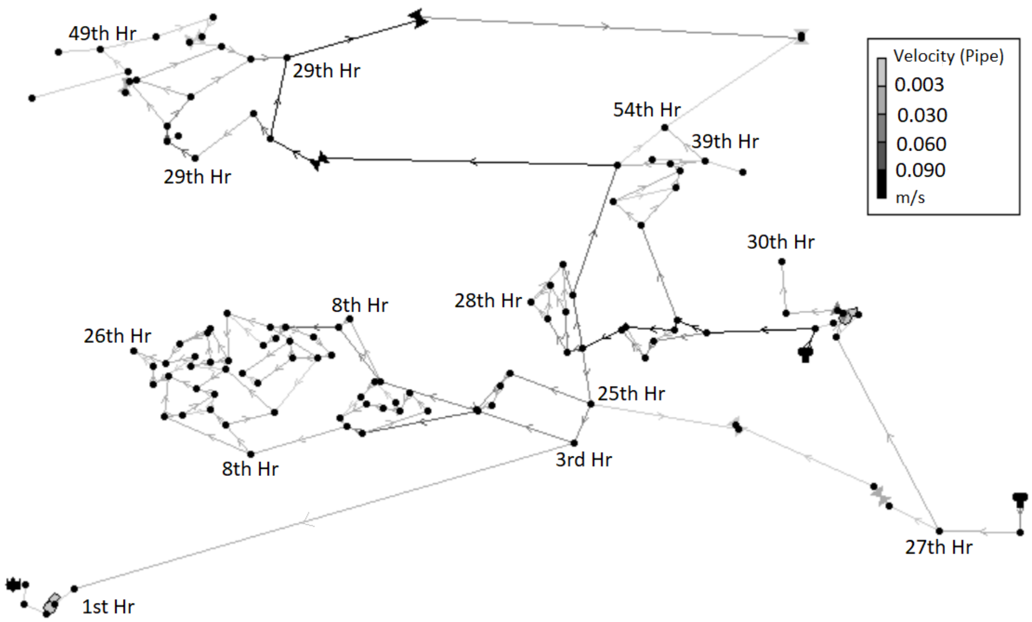

Figure 2-7. Hour of salt intrusion contour of System 6 for the instantaneous salt intrusion event.

System 7 is also a looped WDS having 135 pipes connected by 118 junctions, one tank situated far away from the single groundwater reservoir, and a consistent demand pattern throughout the system. Salt reached the mainline immediately following the instantaneous salt intrusion event, and the other parts of the system were contaminated eventually following geographical sequential order (Figure 2-8).

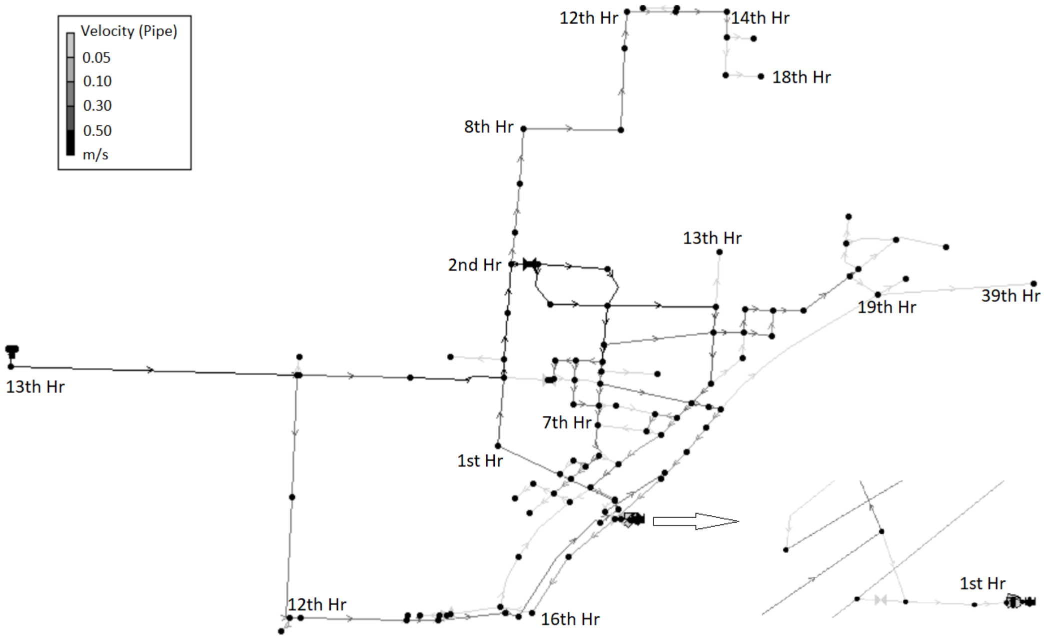

Figure 2-8. Hour of salt intrusion contour of System 7 for the instantaneous salt intrusion event.

System 8 is a looped water distribution system consisting of 394 pipes, 347 junctions, one ground water reservoir, and two tanks. One tank is located middle of the system and the other is located far from the reservoir. Only one demand pattern exists throughout the system, which is mostly continuous except for some hours at night (Table 2-1). For the instantaneous salt intrusion event, salt reached most of the junctions in sequential geographical order; however, salt reached some junctions late due to low demand and far distance from the reservoir (Figure 2-9).

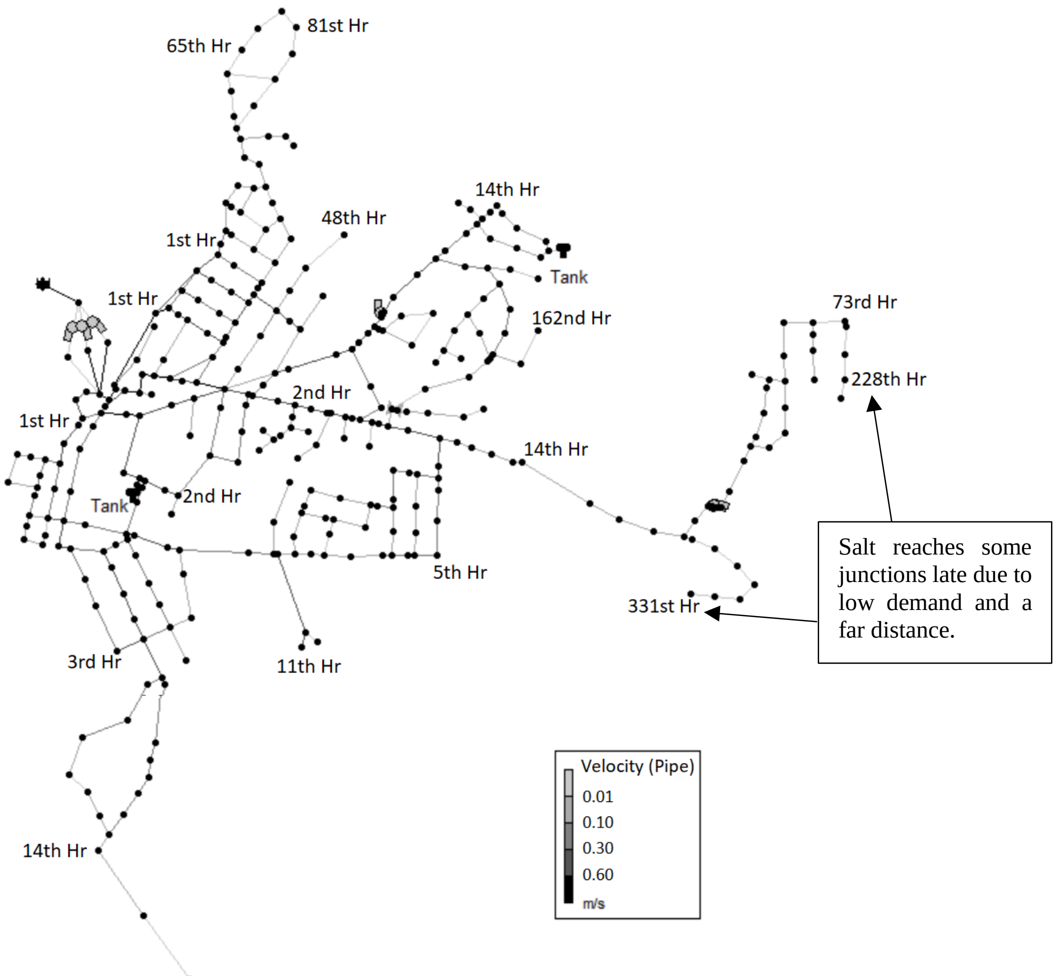

Figure 2-9. Hour of salt intrusion contour of System 8 for the instantaneous salt intrusion event.

System 9 is also a looped water distribution system consisting of 958 pipes, 874 junctions, one ground water reservoir, and one tank directly connected to the pumping station. Water demand throughout the system follows a similar pattern (Table 2-1). Salt reached the junctions in geographical sequential order in the instantaneous salt intrusion event; however, some outer junctions were contaminated fairly quickly compared to others (Figure 2-10).

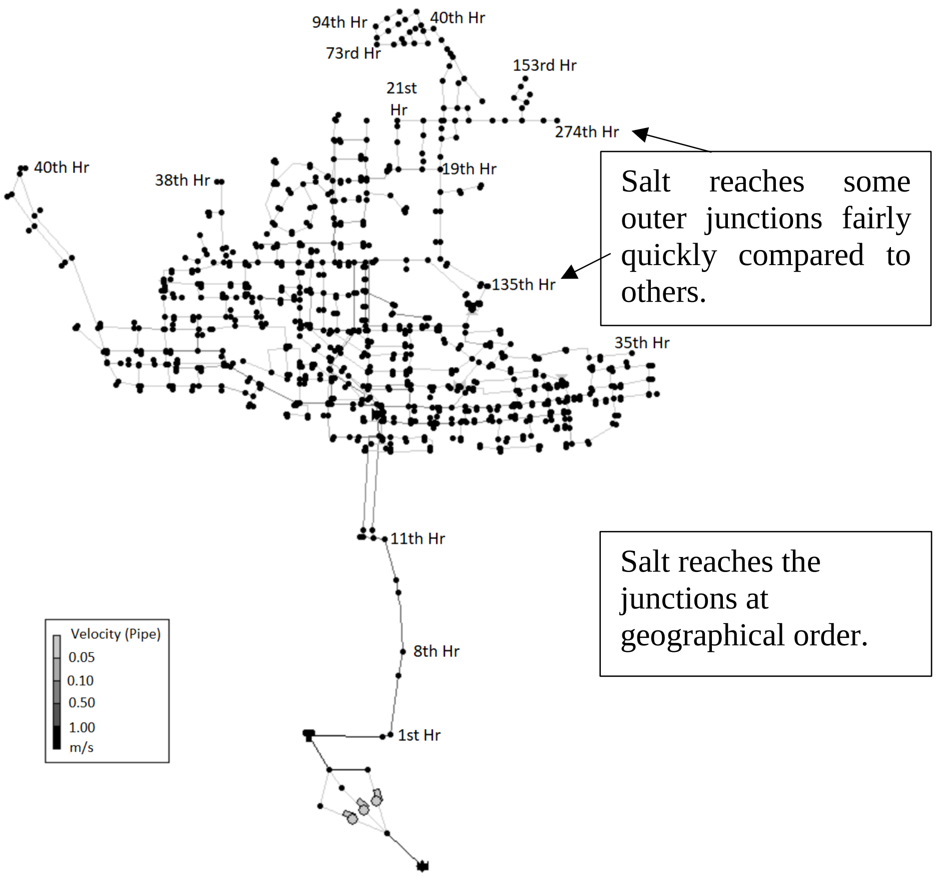

Figure 2-10. Hour of salt intrusion contour of System 9 for the instantaneous salt intrusion event.

System 10 is a large looped distribution system with 14,824 pipes, 12,525 junctions, two ground water reservoirs located very close to each other, and four tanks. Two tanks are directly connected to the two pumping stations and get water from the respective reservoirs simultaneously. The other two tanks are situated in the middle of the system (Figure 2-11). The system has two continuous demand patterns throughout the system (Table 2-1). It was seen that, as expected, salt reached the junctions in sequential geographical order in the instantaneous salt intrusion event due to high velocity values in the pipes (Figure 2-11).

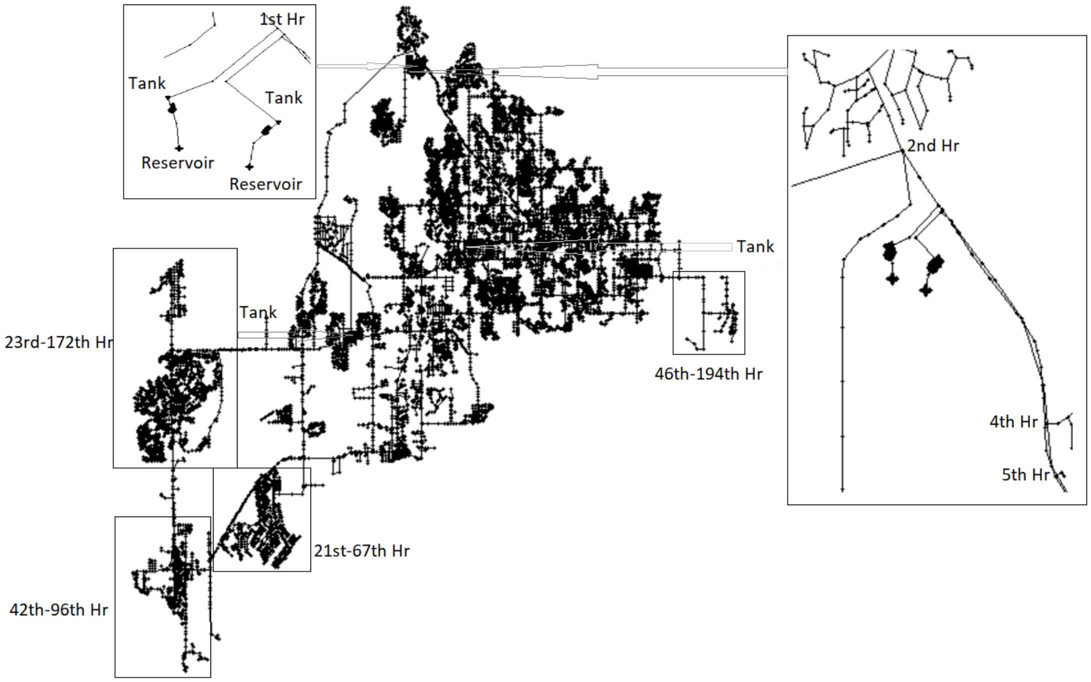

Figure 2-11. Hour of salt intrusion contour of System 10 for the instantaneous salt intrusion event.

System 11 is a comparatively smaller looped WDS with 39 pipes, 19 junctions, one storage tank, one groundwater reservoir, and one consistent demand pattern. The tank is directly connected to the pumping station. Salt reached the entire system in geographical sequential order following the instantaneous salt intrusion event (Figure 2-12).

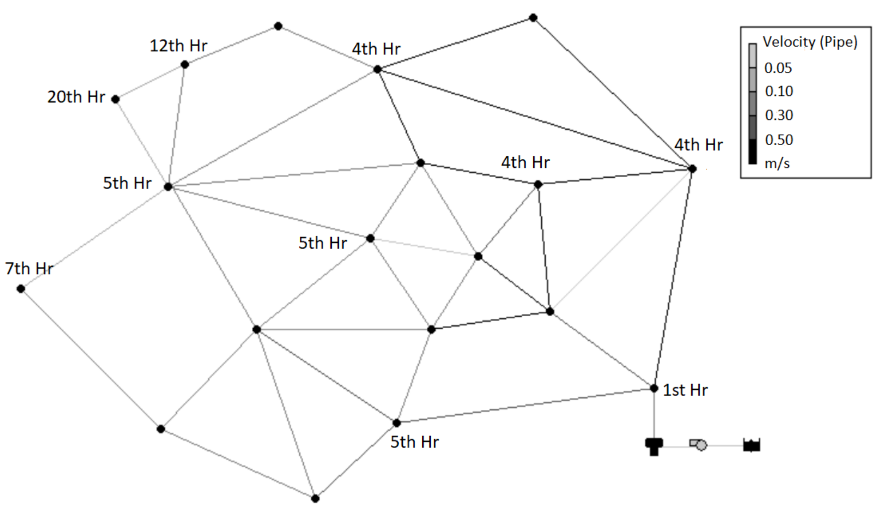

Figure 2-12. Hour of salt intrusion contour of System 11 for the instantaneous salt intrusion event.

System 12 is a branched WDS consisting of 41 pipes connected by 41 junctions, one tank, one groundwater reservoir, and one mostly-continuous demand pattern. The tank position is in the middle of the system. In the instantaneous salt intrusion event, the junctions are contaminated as the salt is transported through the mainline (Figure 2-13).

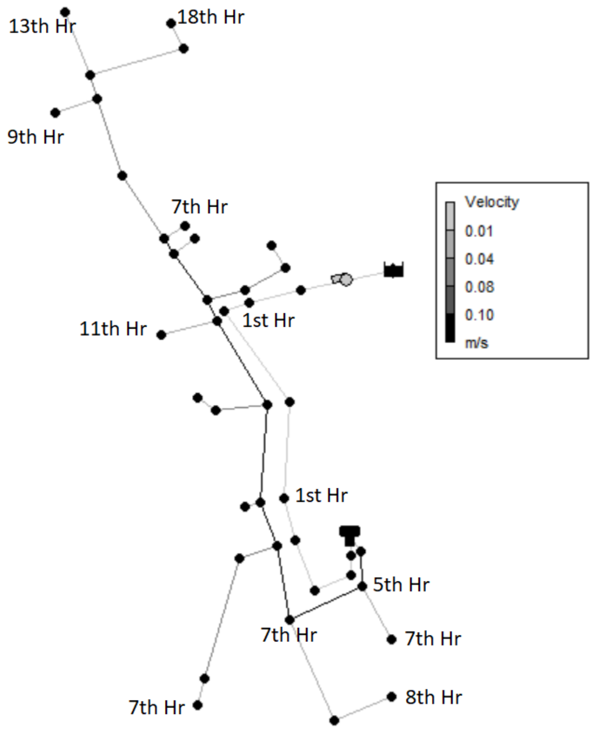

Figure 2-13. Hour of salt intrusion contour of System 12 for the instantaneous salt intrusion event.

System 13 is a geographically flat, looped water distribution system with 551 pipes, 504 junctions, no tanks, four ground water reservoirs (Reservoirs 1-4) pumps on the left of the system, and three surface water reservoirs (Reservoirs 5-7) flowing by gravity with pressure-reducing valves before entering the system on the right side of the system. The system has a typical diurnal demand pattern throughout it (Table 2-1). Salt was modeled as entering through the ground water reservoirs in the instantaneous salt intrusion event and it was observed that salt generally spread from the contaminated sources to the uncontaminated ones on the right (Figure 2-14).

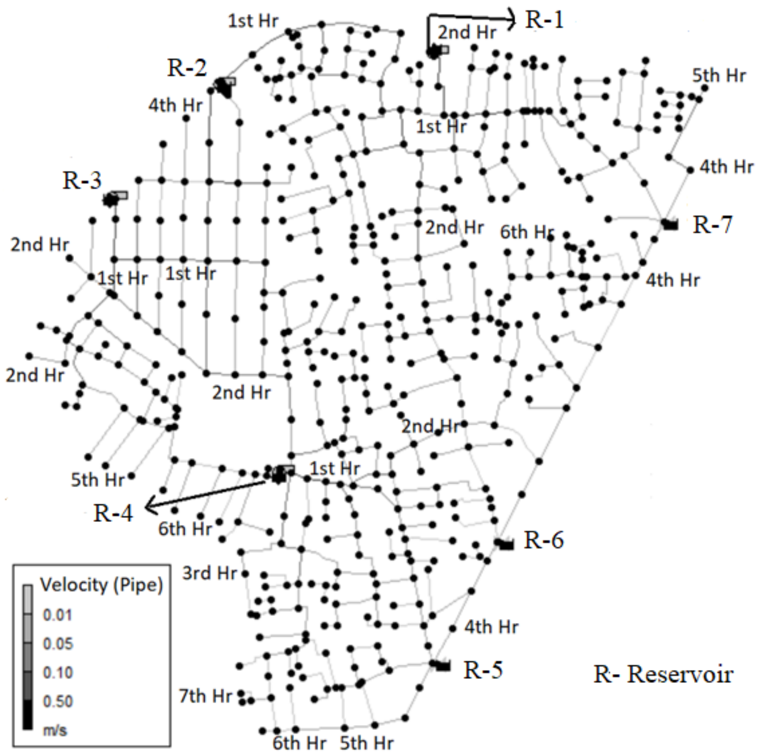

Figure 2-14. Hour of salt intrusion contour of System 13 for the instantaneous salt intrusion event.

2.3.2 Analysis of Gradual Salt Intrusion

Table 2-3 and Table 2-4 represent the state of the systems in terms of the selected junctions' conditions (e.g., contamination arrival hour and the maximum level of contamination) and the system contamination termination hour for the analyzed contamination scenarios of the gradual salt intrusion event. The contamination termination hour refers to the time to clear the system starting at the beginning of the contamination event. Among the twelve contamination scenarios, one or two scenarios for each system were chosen to show the salt percentage throughout the systems at the contamination arrival hour at the 'Beginning Junction' and the 'End Junction'. These contour plots also show the velocity at each pipe.

When System 3 was analyzed for all the scenarios of a gradual salt intrusion event, it was seen that the contaminant spread was not consistent (Table 2-3, Figure 2-15 to Figure 2-17). In S-1, the beginning junction, which is comparatively close to the reservoir, received contamination after several hours of contamination entry (Figure 2-15), and the end junction for this scenario was different from all the other cases (Figure 2-16, Figure 2-17). Possible reasons can be discontinuous demand patterns at the junctions and the pump status. Again, there was a sharp change in the 'Beginning Junction Contamination Hour' in S-10 and S-11 and the 'End Junction Contamination Hour' in S-7 and S-8. This occurred perhaps because of the pump on/off status. It was seen that salt spread was quick through the system at a faster rate of salt entry since the tank is at the far end, away from the mainline (Figure 2-15). In addition, salt reaches some junctions late due to low demand and a long travel distance (Figure 2-16, Figure 2-17). Also, the salt percentage throughout the system did not always reach 100% because the pump was off for some time during the time of reservoir contamination. The maximum percentage of the salt level did not reach the 'End Junction' during the faster rate of salt entry scenarios since the salt concentration became diluted, being mixed with the fresh water before reaching the 'End Junction'.

System 8 showed consistency in all scenarios of the gradual salt intrusion event. The salt spread was similar in all the scenarios (Table 2-3), and the spread was quick through the system since one tank was far away and the other was at the middle of the system (Figure 2-18). The 'End Junction' of the system was consistent throughout all the cases. It was seen that it took several hours for the salt to reach the 'End Junction' after the contamination entry at the reservoir and that during a faster rate of salt entry, many parts of the system were already clean when the 'End Junction' received contamination (Figure 2-19). The 'End Junction' received a similar percentage of salt as the 'Beginning Junction' for a slower rate of salt entry. This happened because salt was entering the system for a longer duration in those scenarios which granted enough time for the salt to reach the 'End Junction' with the maximum percentage of concentration (Table 2-3).

Like System 8, the contaminant spread was similar in all cases for System 9 in the gradual salt intrusion event, and the 'End Junction' remained the same in all the analyzed cases (Table 2-4). It was seen that the time to contaminate the 'Beginning Junction' was delayed because of the longer main line and the tank filling operation (Figure 2-20). And, like System 8, it took several hours for the salt to reach the 'End Junction' after the contamination entry at the reservoir. In addition, during a faster rate of salt entry, many parts of the system were already clean when the 'End Junction' received contamination (Figure 2-21). Since the tank is directly connected to the mainline and salt water got mixed with the fresh water in the tank, the 'Beginning Junction' received a relatively low amount of salt in the faster contamination scenarios. The maximum salt level never reached 100% at the 'Beginning Junction' in any scenario. In addition, the maximum salt level at the 'End Junction' was always less than the maximum level of the salt level at the 'Beginning Junction' (Table 2-4).

Since there are seven reservoirs, System 13 has seven different Beginning Junctions for the gradual salt intrusion event. However, the time documented in Table 2-4 as the 'Beginning Junction Contamination Hour' is the shortest time taken by any of the seven beginning junctions to be contaminated. The End Junction was always the same in all cases. The contaminant spread was similar in all cases for this system like the other looped systems, except for S-1 where the 'End Junction Contamination Hour' showed some irregular values. However, when the 'End Junction' received contamination during the faster rates of salt entry, many parts of the system were already clean (Figure 2-23). Another observation from the contour plots was that the 'End Junction' was situated in the middle, which occurred perhaps because the system has source reservoirs all around it. Like the other systems, at faster rates of salt entry, the salt percentage did not reach the maximum percentage at the 'End Junction'; however, at slower rates the 'End Junction' received 100% salt contamination almost every time (Table 2-4).

Table 2-3. State of Systems 3 and 8 for different contamination scenarios of gradual salt intrusion event.

Scen-ario	**Beginning Junction Contamination hour**		**Maximum Level of Beginning Junction Contamination (%)**		**End Junction Contamination hour**		**Maximum Level of End Junction Contamination (%)**		**Time to Clear (hour)**	
	System 3	System 8	System 3	System 8	System 3	System 8	System 3	System 8	System 3	System 8
S-1	31	1	21	100	66	331	21	44	305	425
S-2	7	1	100	100	56	331	19	84	305	426
S-3	6	1	42	50	56	331	4	36	305	449
S-4	6	1	21	100	56	331	2	97	305	473
S-5	6	1	92	100	56	331	81	99	473	568
S-6	6	1	99	100	56	331	88	100	641	737
S-7	6	1	100	100	56	331	94	100	977	1,072
S-8	6	1	95	100	137	331	95	100	1,736	1,817
S-9	6	2	99	100	137	331	99	100	3,080	3,256
S-10	6	3	99	100	137	352	98	100	5,936	6,112
S-11	79	19	100	100	137	353	99	100	11,648	11,871
S-12	79	19	100	100	137	353	100	100	17,441	17,610

Table 2-4. State of Systems 9 and 13 for different contamination scenarios of gradual salt intrusion event.

Scen-ario	**Beginning Junction Contamination hour**		**Maximum Level of Beginning Junction Contamination (%)**		**End Junction Contamination hour**		**Maximum Level of End Junction Contamination (%)**		**Time to Clear (hour)**	
	System 9	System 13	System 9	System 13	System 9	System 13	System 9	System 13	System 9	System 13
S-1	8	1	16	100	274	10	6	3	306	12
S-2	8	1	23	100	274	9	7	6	306	12
S-3	8	1	82	100	274	9	47	100	330	38
S-4	8	1	73	100	274	9	54	97	353	58
S-5	8	1	90	100	275	9	77	99	447	153
S-6	9	1	95	100	275	9	85	100	637	345
S-7	9	1	96	100	276	9	88	100	972	681
S-8	10	1	97	100	276	9	90	100	1,738	1,449
S-9	10	2	98	100	278	9	91	100	3,176	2,889
S-10	11	3	98	100	280	9	91	100	6,044	5,768
S-11	13	6	98	100	283	10	91	100	11,798	11,520
S-12	16	9	98	100	289	15	91	100	17,556	17,277

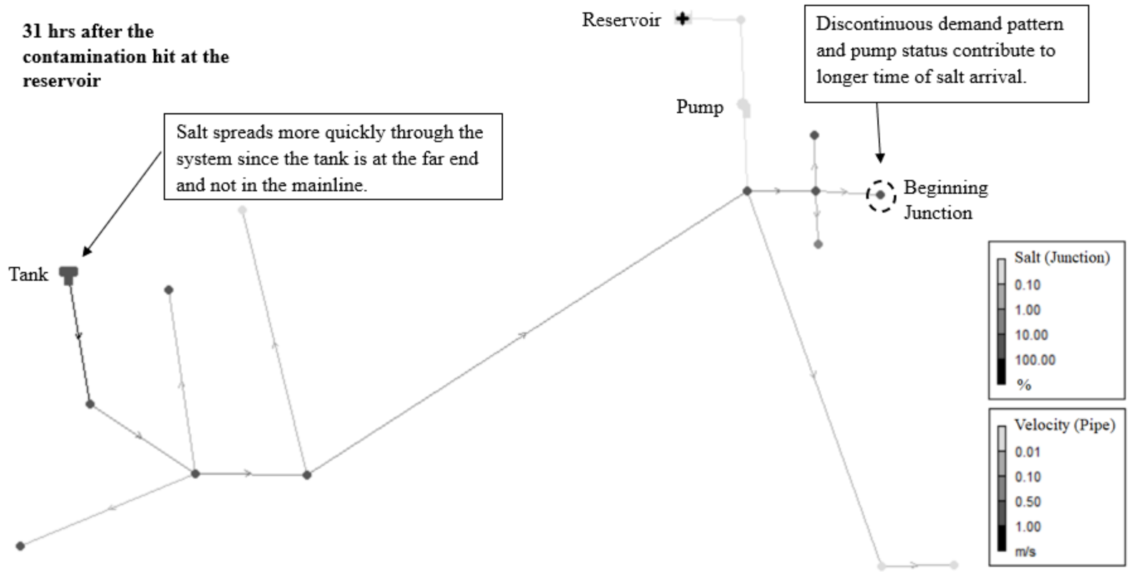

Figure 2-15. Salt intrusion contour of System 3 at Beginning Junction Contamination Hour for S-1 of the gradual salt intrusion event.

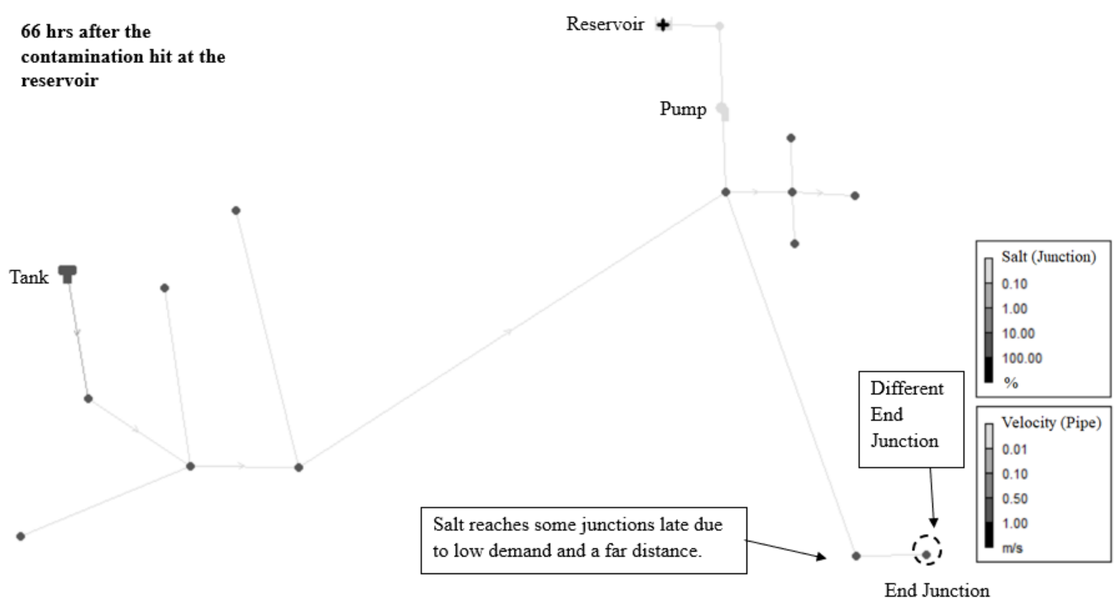

Figure 2-16 Salt intrusion contour of System 3 at End Junction Contamination Hour for S-1 of the gradual salt intrusion event.

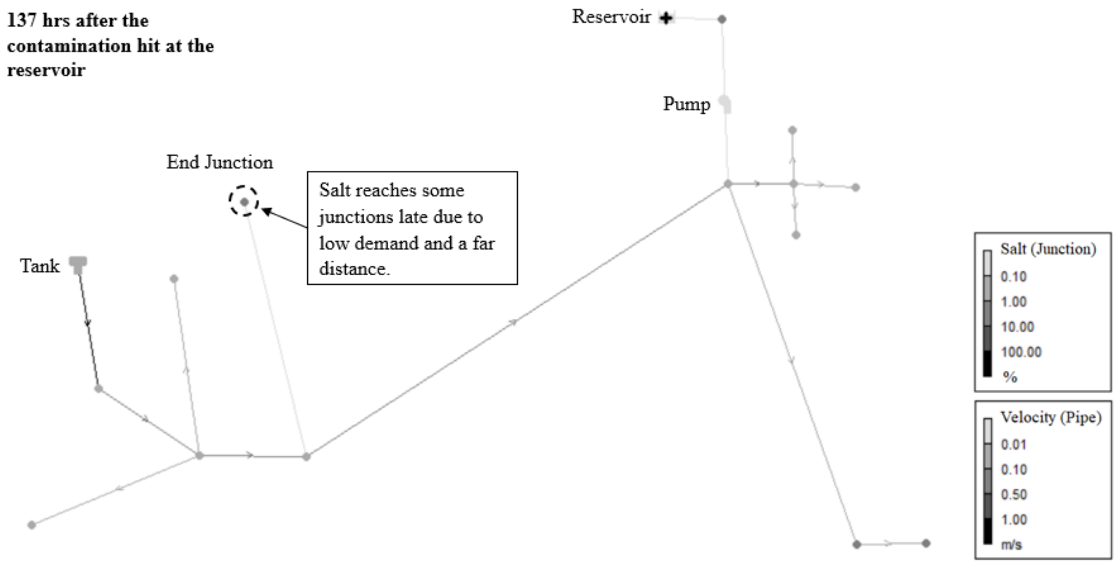

Figure 2-17. Salt intrusion contour of System 3 at End Junction Contamination Hour for S-12 of the gradual salt intrusion event.

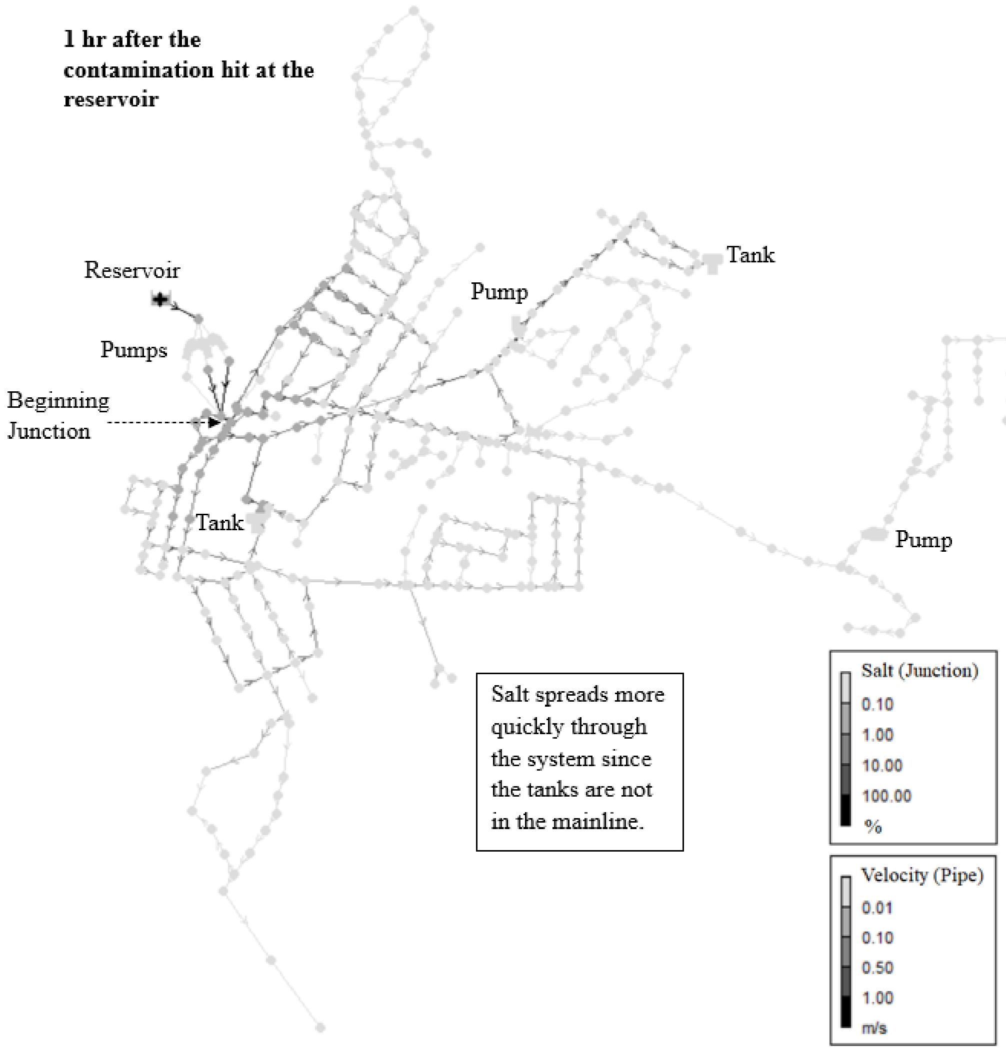

Figure 2-18. Salt intrusion contour of System 8 at Beginning Junction Contamination Hour for S-7 of the gradual salt intrusion event.

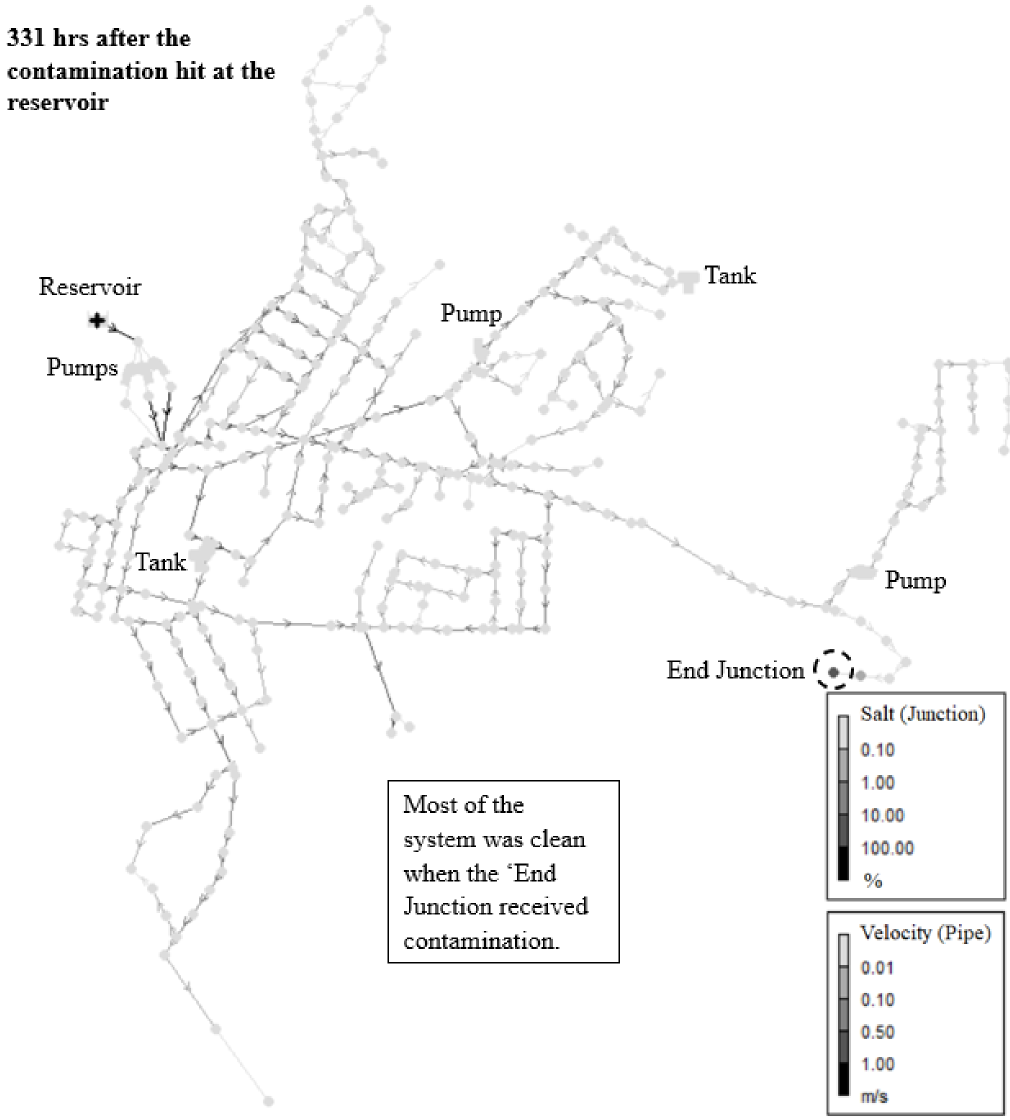

Figure 2-19. Salt intrusion contour of System 8 at End Junction Contamination Hour for S-1 of the gradual salt intrusion event.

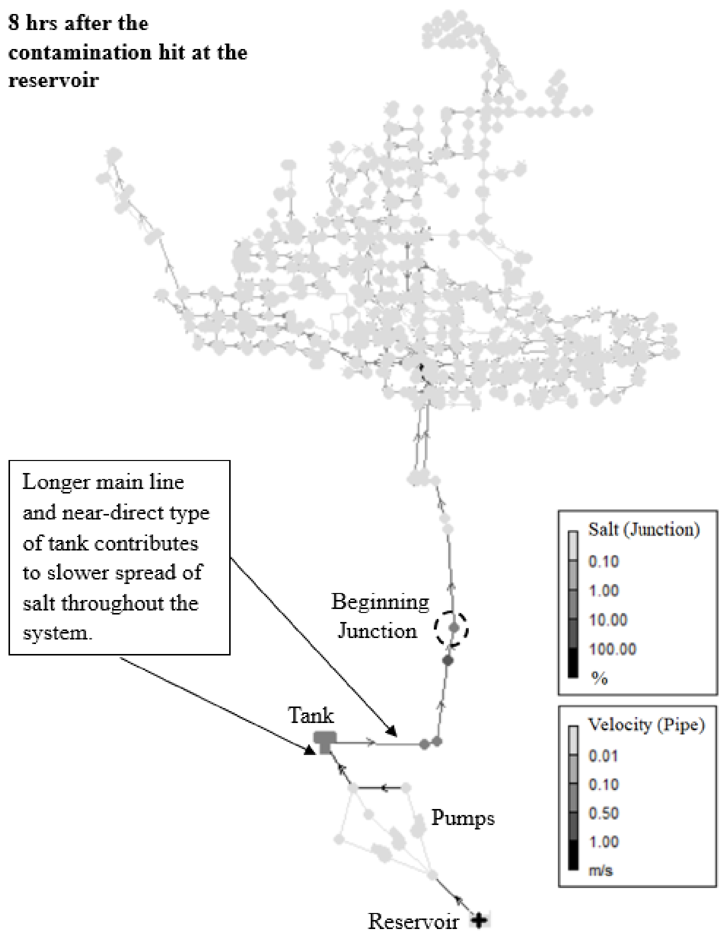

Figure 2-20. Salt intrusion contour of System 9 at Beginning Junction Contamination Hour for S-1 of the gradual salt intrusion event.

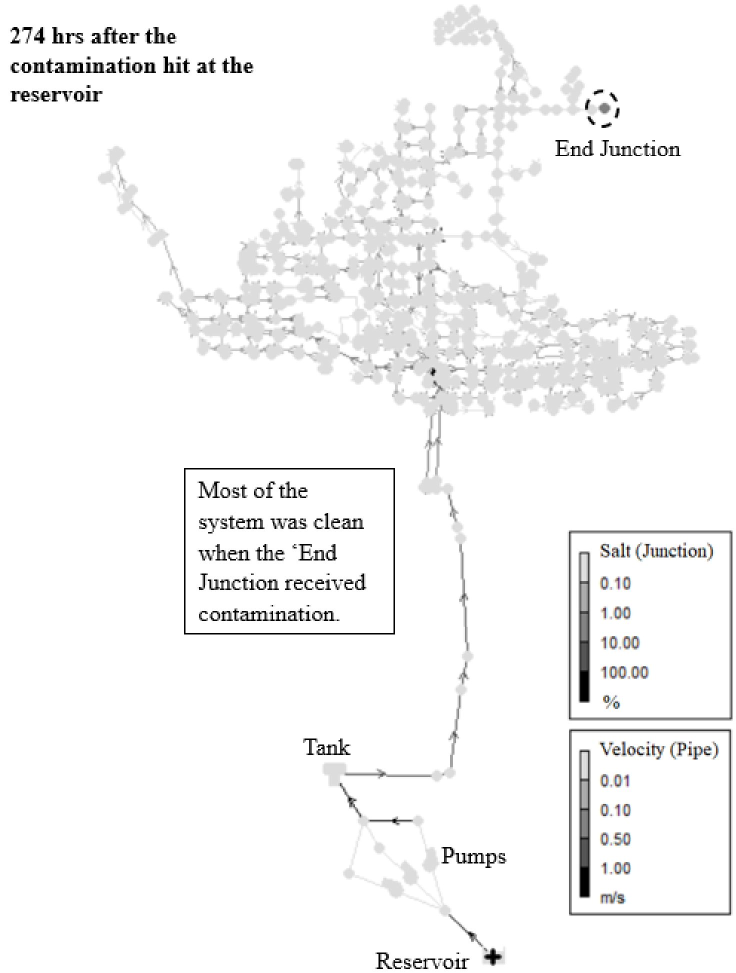

Figure 2-21. Salt intrusion contour of System 9 at End Junction Contamination Hour for S-1 of the gradual salt intrusion event.

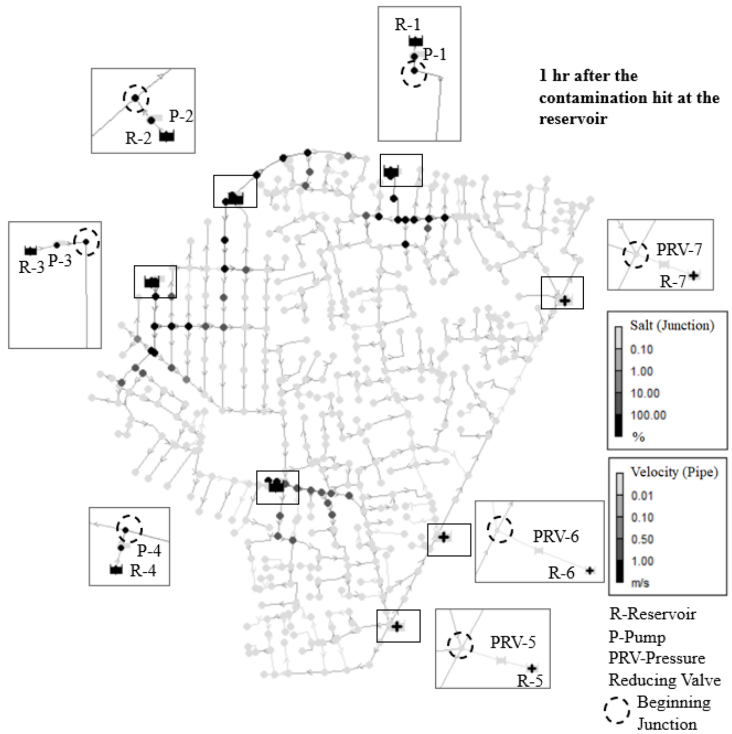

Figure 2-22. Salt intrusion contour of System 13 at Beginning Junction Contamination Hour for S-1 of the gradual salt intrusion event.

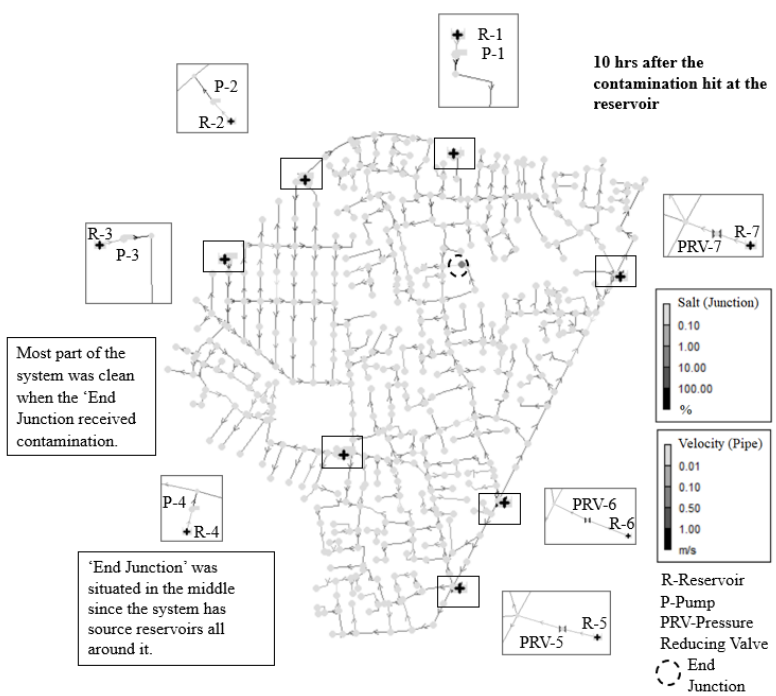

Figure 2-23. Salt intrusion contour of System 13 at End Junction Contamination Hour for S-1 of the gradual salt intrusion event.

2.3.3 Multi-reservoir System Comparison

To analyze the case when some of the reservoirs in a multi-reservoir system are contaminated while the others remain clean, simulations were run for System 13 assuming contamination entry at Reservoirs 1, 2, 3, and 4 for all the scenarios. Unlike the previous cases, these contamination scenarios had four Beginning Junctions since there were four contaminated reservoirs. The 'Beginning Junction Contamination Hour' was the same as before since this time is always the shortest time taken by any of the beginning junctions to be contaminated (Table 2-4, Table 2-5). However, from S-7, the time to contaminate the 'End Junction' was delayed as expected. Also, starting with S-7, different 'End Junctions' were observed and the number of 'End Junctions' gradually increased following the slower rates of salt entry at the reservoir.

Table 2-5. State of System 13 for different contamination scenarios when some of the reservoirs remain fresh.

Scenario	**Beginning Junction Contamination (hr)**	**End Junction Contamination (hr)**	**End Junction ID***	**Time to Clear (hr)**
S-1	1	10	J-490	12
S-2	1	9	J-490	12
S-3	1	9	J-490	35
S-4	1	9	J-490	57
S-5	1	9	J-490	153
S-6	1	9	J-490	345
S-7	1	17	J-160	681
S-8	1	30	J-154, 156	1,449
S-9	2	30	J-57, 68, 163, 154, 156, 474	2,889
S-10	3	30	J- 68, 153, 154, 156, 157, 322, 474	5,768
S-11	6	30	J-41, 68, 153, 154, 156, 157, 160, 312, 322, 395, 453, 474	11,520
S-12	9	30	J-39, 40, 41,68, 153, 154, 155, 156, 157, 160, 312, 322, 358, 362, 395, 451, 452, 453, 474	17,277

*Junctions IDs are mentioned here to show the variability

2.3.4 Comparison Between Systems

Since the systems were unique in terms of their size, orientation, tank position, demand patterns, etc., it was critical to compare the results to find common trends. One common thing among them was that they were analyzed for the same contamination scenarios. Therefore, to compare the systems fairly, the time to clear each system was plotted against the duration of contamination entry in their actual scale and on the normalized scale (Figure 2-24). It was found that each system had a linear response to contamination as expected, which indicates a constant time to clear the system. A linear curve fit was drawn through all the data points to develop a single equation. The linear correlation coefficient was found to be nearly 0.9994 (Figure 2-25).

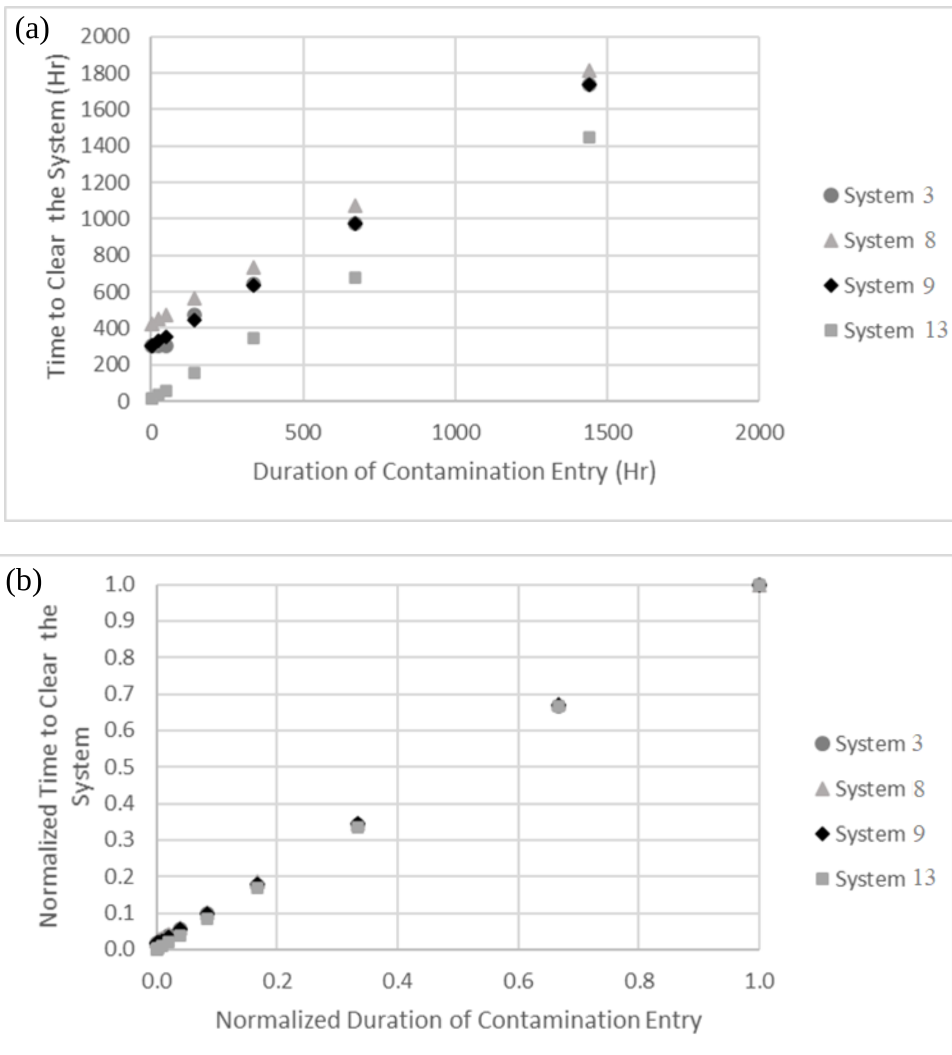

Figure 2-24. Systems comparison in terms of salt contamination termination (a) in actual scale, (b) in normalized scale.

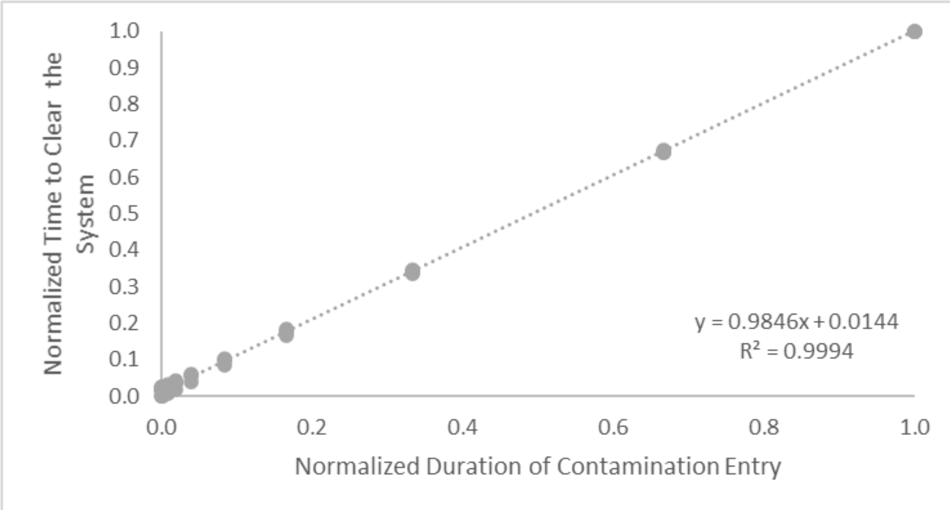

Figure 2-25. The trend line for time to clear any system in terms of salt contamination duration.

2.4 Discussion

Possible managerial actions that could be taken as preventative measures against unhealthy levels of salt consumption among water system users could be the supply of bottled water instead of contaminated distribution system water, flushing of the system with clean water from an uncontaminated source, disposal of contaminated system water into containment ponds to avoid contamination of the environment with excessive levels of salt, or water treatment.

The purpose of this study was to document different types of systems' behavior in events of salt intrusion at the reservoir/s at different rates. It was found that the percentage of salt reaching different parts of the systems at a given time was directly dependent on the demand pattern and the pump operation status. A junction that is geographically nearer to the reservoir might not receive salt right away because of its discontinuous/low demand category. Again, at any reservoir salt contamination event, the highest salt level in any system will depend on the pump status during the time of the salt entry. If salt enters as a short pulse, it can move around the system and contaminate different parts at different times while most of the system is already clean. The amount of salt at the edges of the system will be nearly the same as the source for the slower rate of salt entry only if the tank is directly connected to the reservoir. In addition, for the faster rates of salt contamination, the entire system will not receive the maximum level of salt. The End Junction to receive salt after all other junctions can be at anywhere in the system if it is a part of a multi-reservoir system or has a low or discontinuous demand pattern. Also, in a multi-reservoir system, the 'End Junction' can be different at different salt contamination scenarios and the number of end junctions can increase with the slower rate of salt entry. It was also found that whatever be the type of the system, the time to clear the system from salt contamination linearly correlates with salt entry rate at the reservoir/s.

EPANET can calculate the "water age", or the time it took for a parcel of water to reach any given location since it left the source. Since EPANET does not incorporate dispersion or diffusion, and diffusion being the dominant transport mode in dead ends, the time for salt to reach the dead ends would be faster if diffusion was considered. However, the variation in results would be negligibly different. Additionally, if this study was conducted for any non-conservative contaminant, the contaminant spread would be different- both the maximum level of contaminant percentage and the time to clear the system would be less.

2.5 Conclusions

The following points can be concluded from this study:

1. Salt spread will be similar in any system with a consistent demand pattern under different salt intrusion scenarios.
2. Unlike non-conservative contaminants, salt spreads fairly quickly and the amount is almost the same at the water source and at the edges of any system for a slower rate of salt intrusion since there is no decay in concentration. However, if the tank is directly connected to the mainline, the salt concentration might be different. Also, for a pulse of salt intrusion, the maximum contamination percentage might not reach all the edges.
3. The total time required for salt to reach an entire system is sensitive to outer junction conditions, such as user demand and pipe size. Both user demand and pipe size affect velocity and, therefore, salt concentration.
4. The user demand at dead-ends is important since a high velocity may draw water and subsequently the salt through the rest of the system more quickly.
5. The junction that gets salt last is not necessarily the furthest junction geographically. A junction near the source may be one of the last to get salt since each junction may have a different water use pattern. Also, in a multi-reservoir system, the junction to receive salt later than any other junction can be one in the middle of the system.
6. Pump status is important for time-to-first-contamination since the users will not get any contamination unless the pump is on. Also, the percentage of salt reaching different parts of a system and its arrival time will depend on the pump operation status. Besides, the highest salt level in any system will depend on the pump status during the time of the salt entry.
7. If salt enters a system as a short pulse, it may move around the system and contaminate different parts at different times, even though the rest of the system will become clean.
8. The main line size and the position of the tank is important to the rate of the spread of salt. If the main line has a bigger diameter and/or if the tank is a near-direct type (Wang and Barkdoll 2017), salt will reach the system later than usual. On the other hand, if the tank is located to the side of the system (e.g., System 3), then the tank fills simultaneously with spreading to the users.

9. In a multi-reservoir system, if any reservoir remains fresh during a salt contamination event, contamination might take a longer time to reach all edges of the system and the salt spread will not be the same.
10. For any type of system, the time to clear the system from salt contamination will be linearly correlated to the rate of salt entry at the source.

In any salt intrusion event, water managers should focus on warning the users where salt will reach first since they will be the first ones affected. If the water manager has an earlier understanding of the system, he will know the warning sequence in any salt contamination event. Monitoring salt concentration at the treatment plant can help preventing salt entry in the distribution network. Water supply should be discontinued if the salt concentration is too high in the treatment plant. Since such contamination events can take place in any water system, a method of salt contamination remediation is needed in addition to stopping the water use and flushing the system. If applicable, freshwater sources can be used to flush the system and supply water. Although beyond the scope of this work, this study may be able to guide a flushing program to decontaminate the system.

3 Feasibility of an Environmentally Friendly Method of Contaminant Flushing in Water Distribution Systems Using Containment Ponds

This chapter has been published as a journal paper in "Water Supply" Journal.

[Sheefa, D.E., and Barkdoll, B.D., 2022. "Feasibility of an environmentally friendly method of contaminant flushing in water distribution systems using containment ponds." *Water Supply.*]

3.1 Introduction

Comparative studies have been performed on existing flushing methods including evaluation of flushing to remove contamination (Polychronopolous et al. 2003, Vitanage et al. 2003, Poulin et al. 2010), optimization of hydrant selection for conventional flushing (Wu 2015), use of aggressive flushing for identifying discoloration factors (Boxall et al. 2003), and mobile flushing to prevent secondary water contamination (Kowalski et al. 2015). However, the scope of all these studies was limited to hydrant flushing and no alternatives were introduced. Though 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 gets discharged into the environment and finally ends up in lawns, agricultural fields, water bodies, 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 to obstruct further spread to the surroundings and the impermeable liner will obstruct 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 since 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 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 and Gray 2005, Merricks et al. 2007).

The purpose of this study is to evaluate the performance of a containment pond as a way of water distribution system decontamination for nine real WDSs. Here, the performance is 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 since 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 modeled here for simplicity.

3.2 Procedure

To capture the contaminated water in a containment pond rather than using 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 modeled using the network solver EPANET (Rossman 2000). The proposed procedure is comprised of two phases where 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 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 time to decontaminate the system. This determined the volume of excavation required for the pond. Then the volume discharged from all the additional hydrants to clear the other areas of the system was added to get 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 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. 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. In order to model the pond, for each simulation, discharge was increased until either the pressure was small but positive at any time or location, or any part of the system experienced a reduction in contamination level to a negligible level. 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 contaminants, fire hydrants at the dead ends were modeled as being open to clear the rest of the system. Opening fire hydrants does 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 with the objective of minimizing both the cost and amount of contaminated water discharged into the environment. This was a multi-objective optimization problem where cost was minimized due to typical budget constraints (eq. 1) and the amount of contaminated water put into the environment was minimized (eq. 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.

This optimization was performed by enumeration by putting a pond at three evenly spaced periphery dead end locations.

Pond total cost was comprised of the pond excavation and lining, pumping energy costs, and alternative water source costs. Table 3-1 represents the unit cost per item 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 (1997), 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 the 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 and Wang 2011), and 0.5 L bottles of water would be supplied until decontamination was complete.

For comparison, the base case (i.e., hydrant flushing) was modeled 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 modeled as simultaneously open.

Table 3-1. Unit cost per item for determining the 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	\$0.54/0.5L bottle	The number of water bottles required was determined assuming 55.6% of the total water demand to be domestic water demand (Shammas and Wang 2011). The unit cost per 0.5L bottle was determined based on the average cost of 15 different suppliers.

*Since all the unit costs are within few years, the inflation would be negligible.

3.3 Method Application on Real WDSs

In this study, nine looped real water distribution system models were used (Table 3-2) with systems ranging from 8 to 958 pipes, 6 to 874 junctions, 0 to 7 tanks, different tank positions as per Wang and Barkdoll (2017), 1 to 4 groundwater reservoirs, 0 to 3 surface-water reservoirs, and various ranges 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, i.e., containment ponds. The basis for choosing a pond location was the lowest cost and least environmental impact.

Table 3-2. Primary data of the water distribution systems.

System	No. of Pipes	No. of Junctions	No. of Tanks	Position of tank/s*	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

*Near-Direct (ND), Near-System (NS), Far-System (FS), Mid-System (MS) as per Wang and Barkdoll (2017)

3.4 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 3-3, Appendix A). In comparatively smaller and completely 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 contaminated water discharge to environment by more than 80%, and at least one of the pond locations 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. Appendix A shows 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 3-4. 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 A.1. as an example). Table 3-4 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 3-5 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 \$0.10M (System D) to \$64.59M (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 3-1 (continued)) and all the systems' plots have been combined for comparison (Figure 3-2). It was seen that the range of both axes was 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 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 the base case V_{te} is the volume of contaminated water discharged to the environment from those hydrants (Table 3-6). The base case cost ranged from \$0.22K (System H) to \$48.56K (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 3-3). 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 3-3 was utilized. From Figure 3-1 (continued), 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 the figure is 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 due to the complex hydraulic characteristics of the systems. For the rest of the systems (i.e., System 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} has also been plotted for ponds at different locations and hydrant flushing alone to analyze the results based on other parameters (Figure 3-4). 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 3-4 was determined to be the best option. Results were negligibly different compared to total cost analysis (Figure 3-3) 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 locations for System D and System E were Pond Location 1 and Pond Location 3, respectively (instead of Location 2 and Location 1, respectively, when pond construction cost was considered). From this outcome it can be concluded that a tradeoff exists for an optimal pond location in which some locations might be better from an economic point of view, while others will be better from an environmental perspective.

Table 3-3. Reduction of contaminated water to environment (%) after adding pond and 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 3-4. Volume of pond and time to clear the entire system with hydrants opened when needed.

System	Pond Volume (m^3)			Time to clear the system (hr)		
	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 3-5. Pond total cost and environmental discharge for different pond locations.

System	Pond Total Cost* ($M)			Discharge to the Environment, V_{te} (M Liter)		
	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

*Pond total cost includes pond construction cost, pumping cost, and bottled water cost as an alternative water source.

Table 3-6. Associated cost and volume of contaminated water to the environment during conventional 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 as an alternative water source

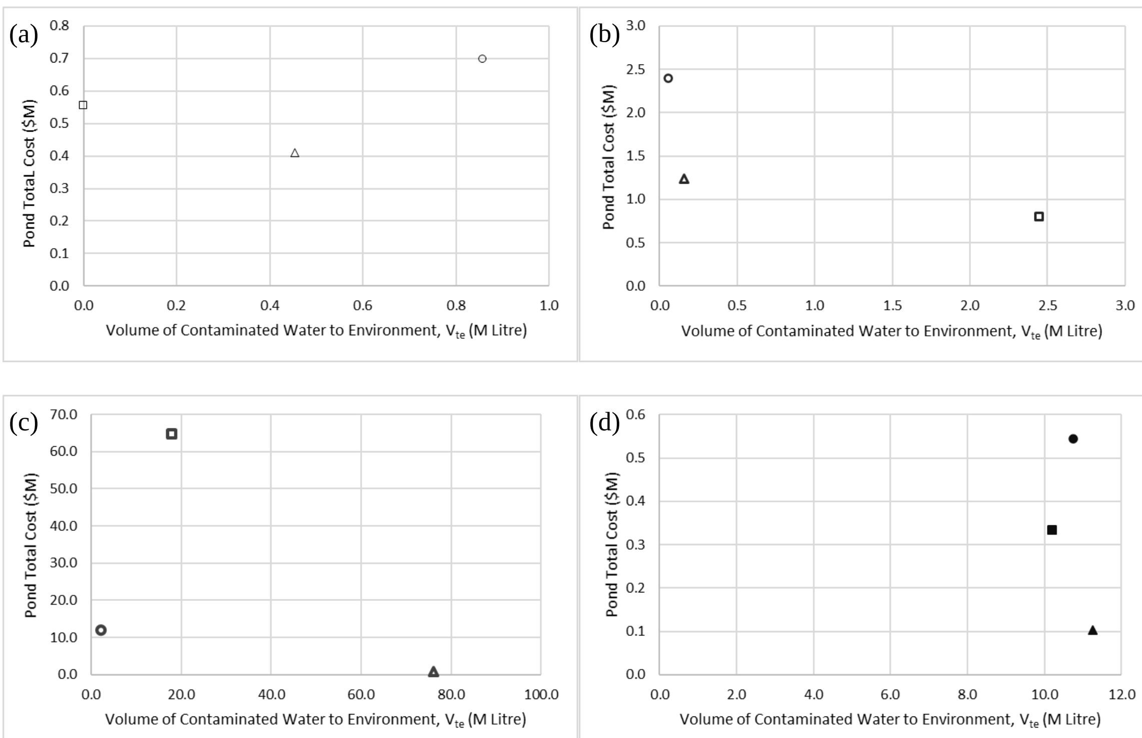

Figure 3-1. Pond total cost vs. volume of contaminated water to environment corresponding to (a) System A, (b) System B, (c) System C, (d) System D, (e) System E, (f) System F, (g) System G, (h) System H, and (i) System I.

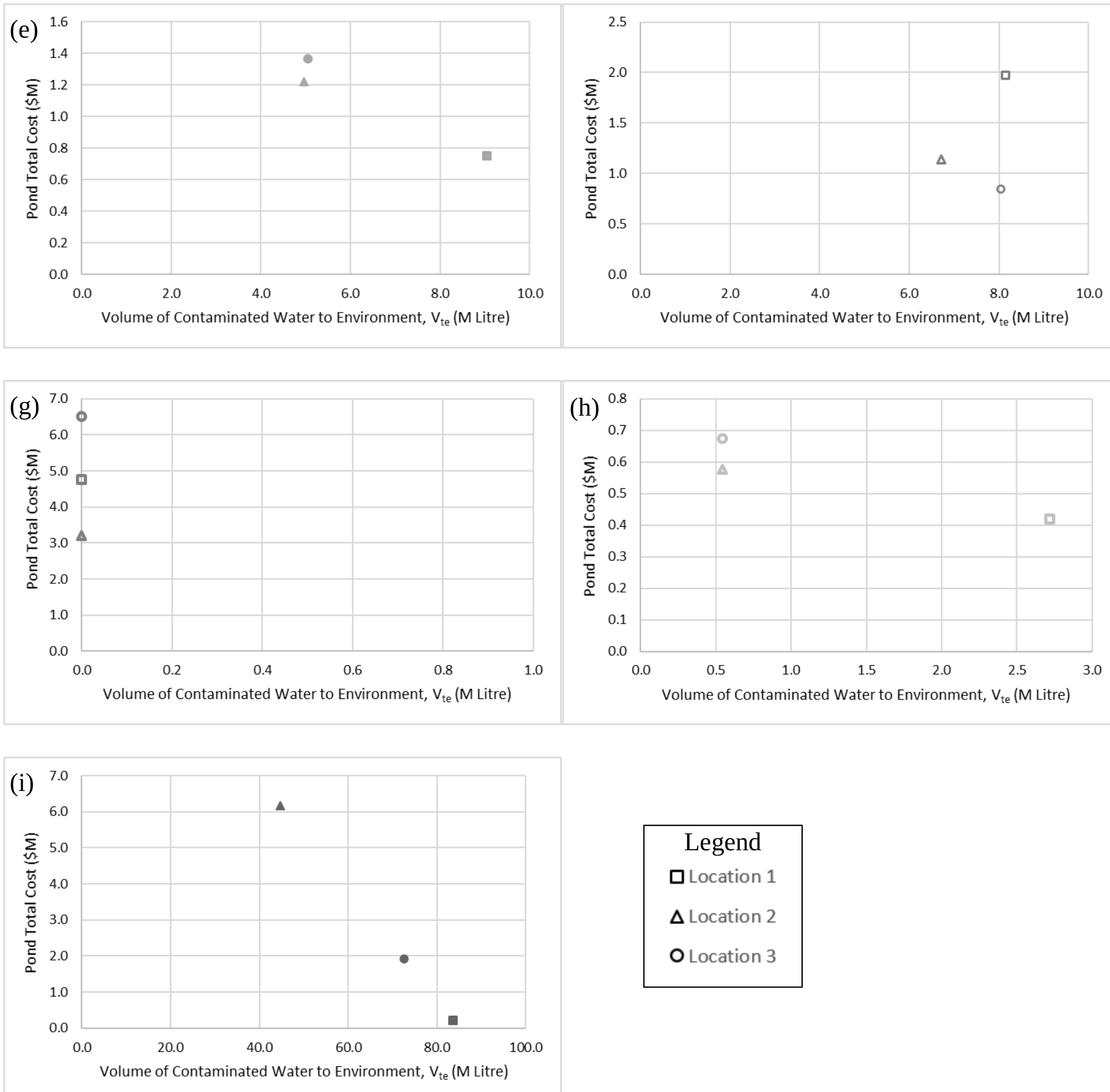

Figure 3-1 (continued). Pond total cost vs. volume of contaminated water to environment corresponding to (a) System A, (b) System B, (c) System C, (d) System D, (e) System E, (f) System F, (g) System G, (h) System H, and (i) System I.

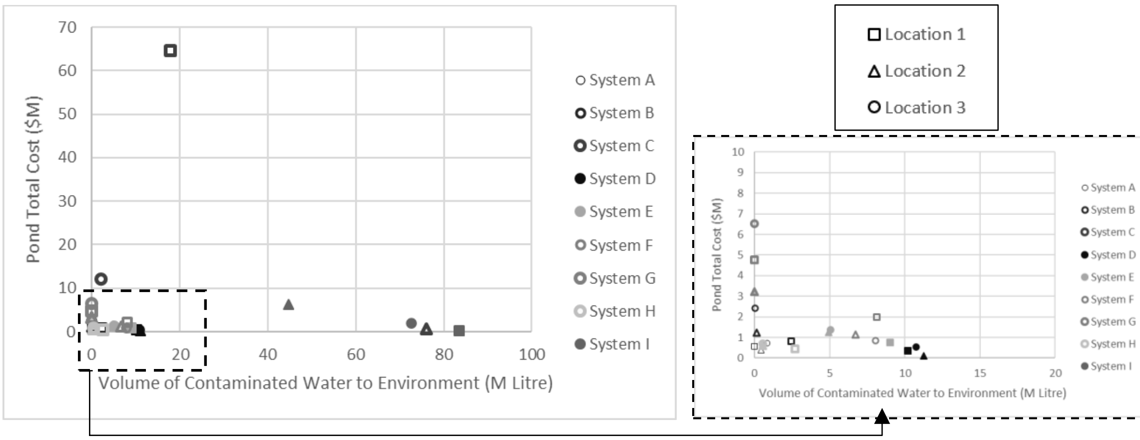

Figure 3-2. Pond total cost vs. volume of contaminated water to the environment for different pond locations.

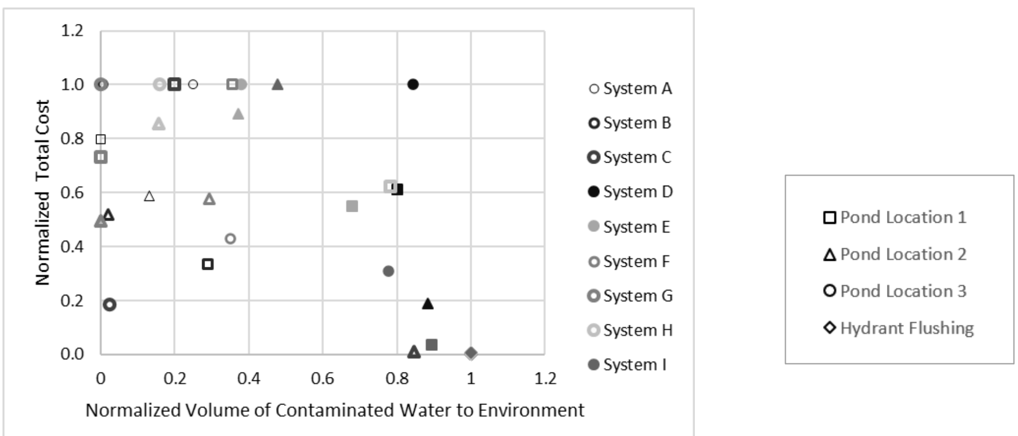

Figure 3-3. Normalized pond total cost vs. normalized volume of contaminated water to the environment for different pond locations.

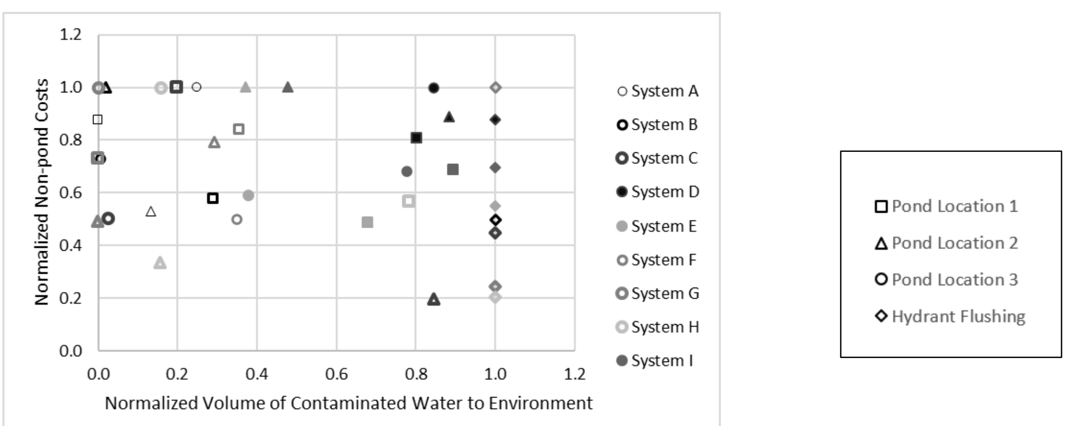

Figure 3-4. Normalized non-pond costs vs. normalized volume of contaminated water to environment for different pond locations.

3.5 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 the optimal location of the containment pond is system-dependent.

3.6 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. Before selecting the pond location all the outer corners of the system should be studied.
4. For some systems, containment pond location may vary 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.

4 Comparative Life Cycle Assessment Study for Water Distribution System Decontamination Using Fire Hydrants and a Containment Pond

This chapter is under review as a journal paper in "Water Supply" Journal at the time of this dissertation submission.

4.1 Introduction

For evaluating the environmental footprint of a WDS decontamination option, Life Cycle Assessment (LCA) is an appropriate tool that is globally used to systematically analyze the potential environmental impacts of products, processes, or systems throughout their life cycles (Huntzinger and Eatmon 2009). For choosing the best option for WDS decontamination, Sheefa et al. (2021) studied the LCA of hydrant flushing and flushing using a pond and found that the use of a pond can reduce the environmental impact by 17.6%. However, this result is applicable only for the assumptions made in that study. The major limitations of the study are (1) the assumption of contaminated water being discharged only to the agricultural fields during hydrant flushing and (2) exclusion of transportation of the items while doing LCA. The current study was conducted to broaden the scope of Sheefa et al. (2021).

The aim of this study was to extend the research scope of Sheefa et al. (2021) so that the results include more variables and can help the water managers to decide the best decontamination option. The study was conducted for four scenarios based on the contaminated water discharge during hydrant flushing. The scenarios are representative of rural water systems, urban water systems, and partly rural and partly urban water systems. Furthermore, a sensitivity analysis was performed to observe the resulting changes in the overall environmental footprint for different input variables.

4.2 Materials and Methods

4.2.1 Investigated System

A WDS can be branched or looped consisting of water source(s), pump(s), pipes, storage tank(s), control valve(s), and fire hydrants. The system model investigated in this study and the assumptions made about the contamination of the system are the same as Sheefa et al. (2021). It is a real, looped water system consisting of one groundwater source, three pumps, 958 pipes, one storage tank, and 280 fire hydrants at the dead ends and/or one containment pond away from the water source (Figure 4-1), and water demand of 1.3×10^6 L/day. Before running the decontamination procedures, the entire system was assumed to have the same concentration of salt. Salt can intrude into groundwater aquifers and also wash into surface water sources from deicing applications on roads. The decontamination procedures were examined using EPANET (Rossman 2000). From the EPANET output, it was found that hydrants took 119 hours to fully decontaminate the system, and the containment pond took 91 hours with the help of some hydrants.

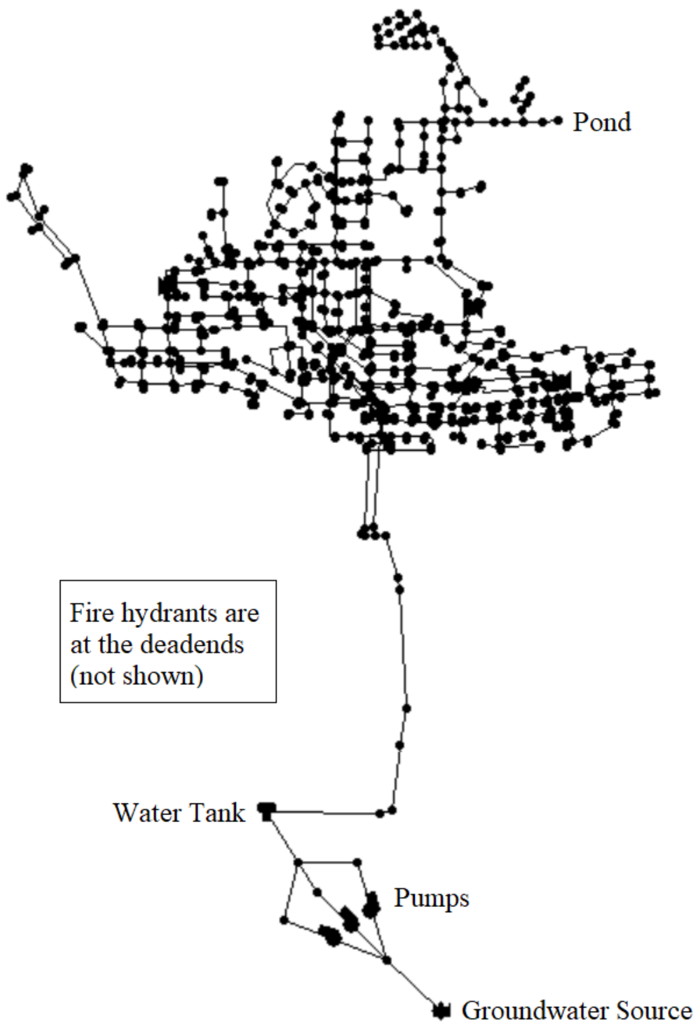

Figure 4-1. Investigated system (same as Sheefa et al. 2021).

4.2.2 Goal and Scope Definition

Decontamination of a WDS using hydrants involves sequential or non-sequential closing of the valves at the consumer ends, flushing the pipes with the clear water from a clean water source, and discharging the contaminated water to the surroundings. By contrast, decontamination using a containment pond involves closing all the valves at the consumer ends, flushing the pipes with clean water from the water source, discharging the contaminated water to a pond lined with impermeable material, and opening hydrants at the dead ends in regions where the pond alone cannot sufficiently flush the system. The time to decontaminate the system depends on the chosen decontamination option. During both the decontamination procedures, the pumps at the water source keep working based on the system design, and the community water demand is met from an alternative water source, e.g., bottled water.

This comparative life cycle assessment aims to evaluate the environmental footprint caused due to a WDS decontamination using (1) only fire hydrants and (2) a containment pond with hydrants where needed. The appropriate functional unit, or functional goal, for this study is complete decontamination of the system i.e., no trace of the contaminant will remain at anywhere of the system. The study is a 'cradle-to-gate' LCA, i.e., it covers all relevant product and process steps from raw material production to the use stage. For the hydrant flushing option, the scope comprises the energy usage during the pump operation, production and distribution of the alternative bottled water, and the environmental impact caused due to the contaminated water discharge. The scope of the decontamination using the containment pond option comprises the energy usage during pump operation, production and distribution of the alternative bottled water, the construction of the pond (excavation and lining), and the environmental impact caused due to the contaminated water discharge through the opened hydrants. Since hydrants are present in most water systems, the installation of hydrants was not included within the scope of the study. By contrast, a containment pond is not a common component of a water system, so including the construction of the containment pond was a requirement.

4.2.3 System Boundaries, Model Assumptions and Data Sources

The study was conducted for four different scenarios based on contaminated water discharge during hydrant flushing (Table 4-1), where the WDS was assumed to be contaminated with salt. In Scenario 1, all the contaminated water was assumed to be discharged to agricultural land to represent a rural water system. To represent an urban water system, all the contaminated water was assumed to be discharged to concrete roads and lawns in Scenario 2 and Scenario 3, respectively. In Scenario 4, contaminated water was discharged to the agricultural lands, concrete roads, and lawns in different proportions, to represent a partly rural and partly urban area. It was assumed that an area of 100 m by 100 m land in front of each hydrant was exposed to contaminated water. The decontamination using a containment pond and hydrants was also analyzed for these scenarios to compare the results. Since it is a 'cradle-to-gate' LCA study, the use of the pond in one contamination event was considered and the fate of the contaminated water in the pond was not included within the system boundary. Input categories and the corresponding values used for the pond construction are given in Table 4-2. The pond volume was determined from the EPANET output, and the depth was assumed to be 2.4 m to ensure proper management (USDA 1997). It was assumed that the pond would be lined with high chemical resistive standard 60 mil HDPE liner (Davis et al. 2012, Shi 2013, Minnesota Stormwater Manual 2021) to prevent infiltration of the contaminated water to the ground. It was also assumed that the raw HDPE was transported to the manufacturing site via rail and the finished product was transported to the pond site via truck. In all the scenarios, the basic water need of the users, which was assumed to be 30% of the total water demand of the system (Knight 2003, Watkins 2006, Ramulongo et al. 2017), was met by supplying bottled water in typical 0.5 L plastic bottles. Input categories and the corresponding values used for producing a 0.5 L plastic bottle are given in Table 4-3. Raw PET was assumed to be transported to the manufacturing site via truck where it underwent the process of stretch blow moulding to produce plastic bottles and was filled with water. Then the packaged water bottles were assumed to be transported to storage via truck and were finally transported to the distribution center via diesel cars.

Table 4-1. Studied scenarios based on exposure of the contaminated water during hydrant flushing.

Scenario	**Description**
Scenario 1: Rural lands	Contaminated water discharge only to agricultural lands during hydrant flushing.
Scenario 2: Urban Roads	Contaminated water discharge only to concrete roads during hydrant flushing.
Scenario 3: Urban Lawns	Contaminated water discharge only to lawns during hydrant flushing.
Scenario 4: Combined (Partly Rural, Partly Urban)	Contaminated water discharge to agricultural lands, concrete roads, and lawns at different proportions during hydrant flushing.

Table 4-2. Summary of inputs for the containment pond construction.

Input	**Unit**	**Quantity**	**Data Source**
Volume of excavation	m^3	7012	EPANET output
Depth of pond	m	2.4	USDA (1997)
Standard 60 mil HDPE liner	kg/roll*	1770	Local supplier
Transportation distance of raw HDPE to manufacturing site via rail	km	604	Shi (2013)
Transportation distance of liner to the pond site via truck	km	48	Shi (2013)

*Standard roll is 1154 m^2

Table 4-3. Summary of inputs for a 0.5 L plastic water bottle.

Input	**Unit**	**Quantity**	**Data Source**
PET Resin	kg	0.0191	Tamburini et al. (2021)
Water	L	0.5	-
Transportation distance of raw PET to manufacturing site via truck	km	200	Botto (2009)
Transportation distance of packaged bottled water to storage via truck	km	365	Botto (2009)
Transportation distance of packaged bottled water from storage to user via diesel cars	km	10	Botto (2009)

Exposure of saline water to agricultural lands can have deleterious effects including inhibition of plant growth. From previous studies, it was found that salinity in agricultural lands can reduce the crop yield by 16-25% (El-Fadel et al. 2018, Dam et al. 2019). So, in Scenario 1, it was assumed that the crop yield in the salt contamination exposed area was reduced by 25%, and hence the same area of land at some other place was needed to be prepared for crop production to meet that lost 25% of crop demand. To grow the crop in that extra land, conversion of the land to agricultural land, planting, harvesting, use of fertilizer, and plant protection were required as input categories for the LCA. The system boundary for this scenario is shown in Figure 4-2 (a, e), and the input values used for the extra crop production are given in Table 4-4.

Exposure of saline water to concrete roads can initiate surface scaling, surface spalling, and/or corrosion of steel reinforcement (Sun et al. 2002, Vorobieff 2005, Haynes et al. 2010, Bassuoni and Rahman 2016). Since weight loss of concrete can be 50% higher in a saline environment (Sun et al. 2002), it was assumed that 50% of the contamination exposed area will be affected (i.e., 50% weight loss) and will experience surface spalling and thus will require one extra maintenance event within its service-life. It was also assumed that the affected road slab had a depth of 195 mm (Loijos et al. 2013), and the thickness of the spall was 1/3 of the depth and thus would require a partial depth repair (Jung et al. 2008). Partial depth repair of concrete is done in four steps- using a diamond blade saw to cut the affected area, removing damaged concrete, sandblasting to clean, and finally patching concrete with the help of an adhesive. It was assumed that one sq. m area can be repaired in 15 minutes where the repairing steps require the same time interval. It was also assumed that a 49 HP diamond blade saw was used to cut the affected concrete area and a 3/8" air compressor nozzle working at 100 psi was used for sandblasting. Finally, 0.25 mm epoxy resin (Jung et al. 2008) was assumed to be placed to patch the new concrete. The system boundary for this scenario is shown in Figure 4-2 (b, f), and the input categories for the partial depth repair and the corresponding values used in this study are summarized in Table 4-4.

Exposure of saline water to roadside vegetation and lawns can initiate damage and reduction in yield, root, and shoot growth (Dudeck et al. 1993, Pasternak et al. 1993, Marcum and Murdoch 1994, Chen et al. 2009, Cooper et al. 2014, Badawy et al. 2018). Dudeck et al. (1993) found that the presence of salinity can reduce the top growth of some types of grass up to 50%. For this study, it was assumed that 50% of the contamination exposed lawn area was severely affected and the sod in that area needed to be replaced. Hence, the same area of sod needed to be produced in a sod farm. The system boundary for this scenario is shown in Figure 4-2 (c, g), and the summary of input used in this study is given in Table 4-4. Grass seeds were assumed to be grown at a different site than the sod farm and later were transported to the sod farm via single-unit diesel truck. Both ammonia and lime were included within the system boundary as fertilizer requirements. Since frequent mowing is essential for sod production (Kaiser and Ernst 2019), it was also included. Based on Smetana and Crittenden (2014) and SodLawn (2020), it was assumed that it took one year for the sod to be matured and ready for harvesting, and finally it was transported to the site via single-unit diesel truck.

In Scenario 4, it was assumed that half of the WDS was from a rural region and the remaining half was urban locality. Hence, half of the contaminated water discharged from the hydrants ended up in agricultural fields and the remaining half was assumed to be equally spread in concrete roads and lawns. The system boundary for hydrant flushing and decontamination using containment pond and hydrants are shown in Figure 4-2 (d, h), and the input categories are similar to Scenarios 1, 2, and 3, which are given in Table 4-4.

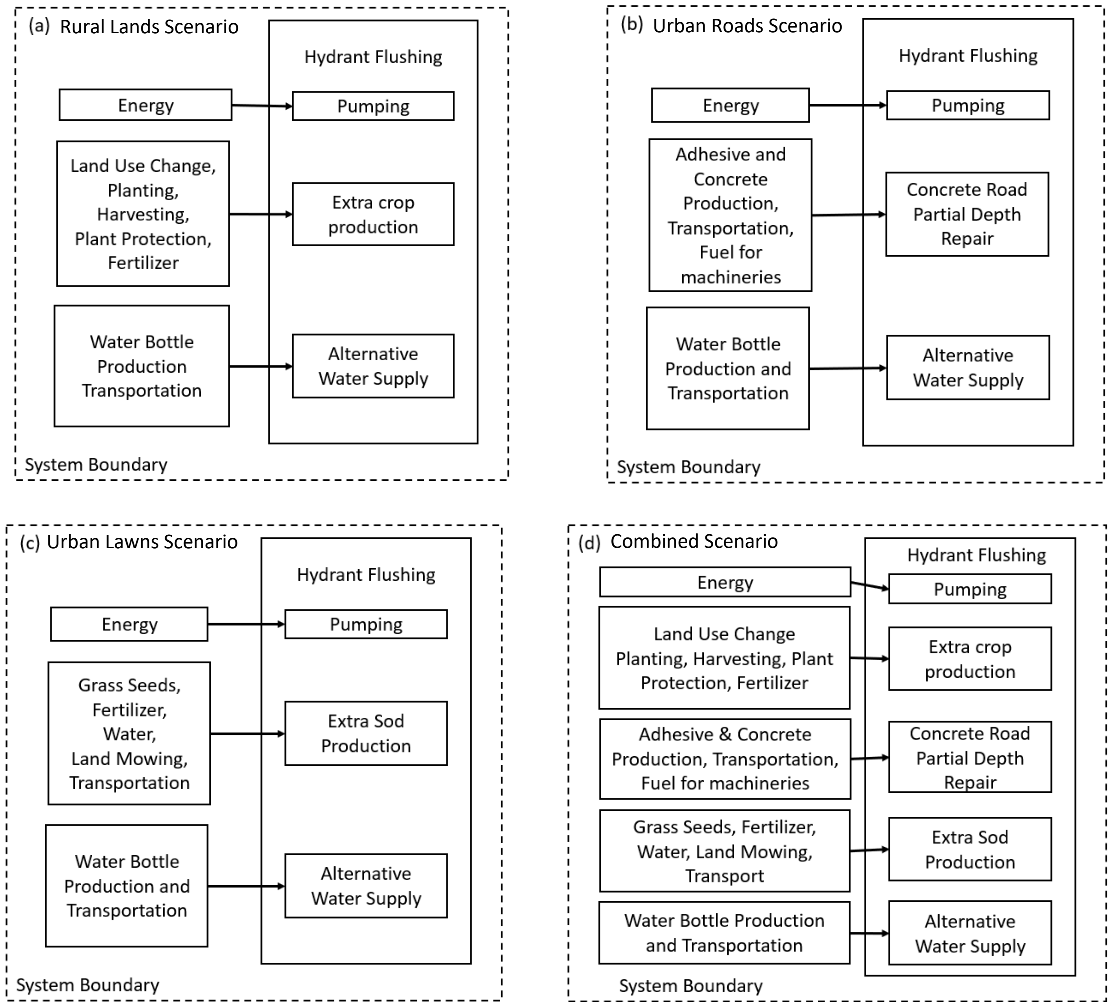

Figure 4-2. System boundaries used in the LCA of the WDS decontamination using hydrants (a, b, c, d) and a containment pond and hydrants (e, f, g, h) under various scenarios.

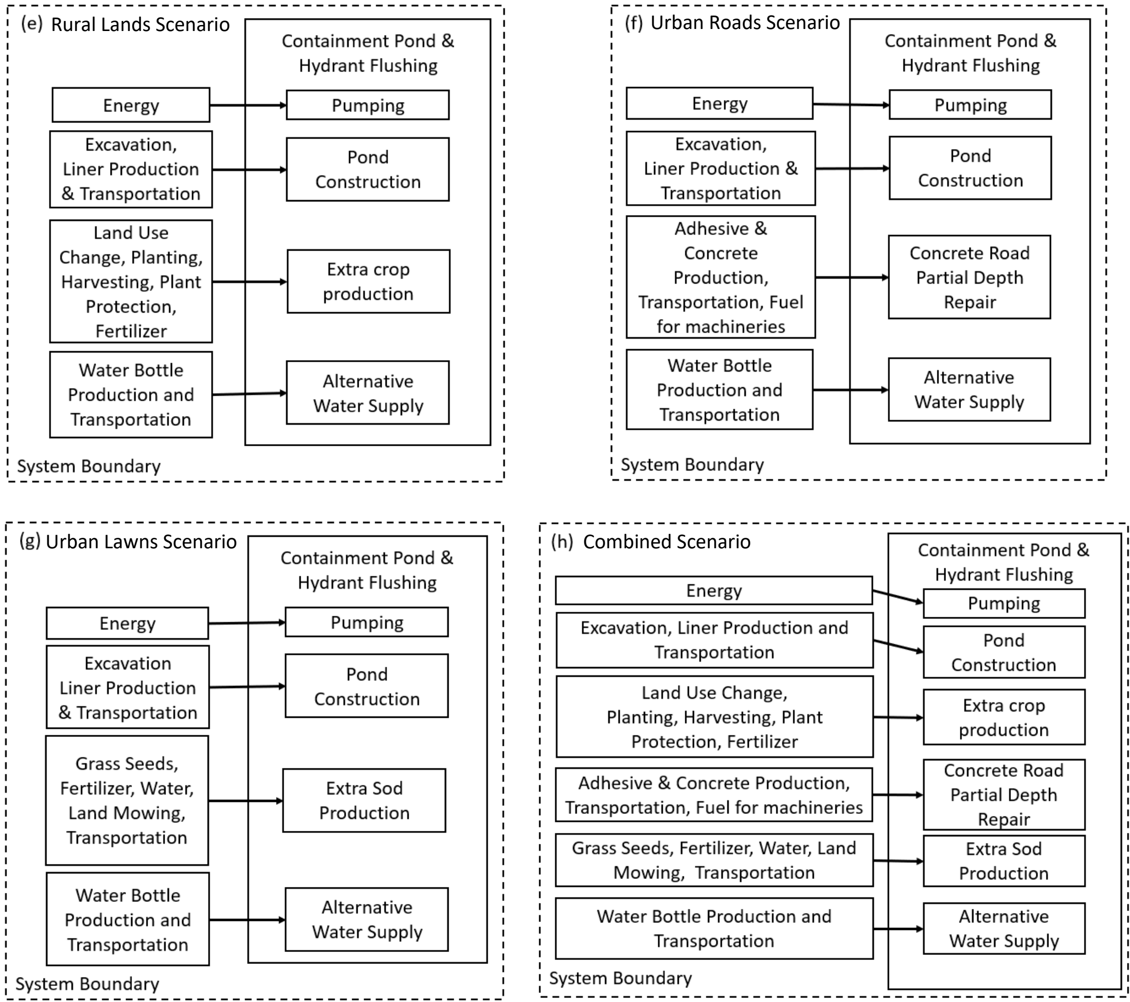

Figure 4-2 (continued). System boundaries used in the LCA of the WDS decontamination using hydrants (a, b, c, d) and a containment pond and hydrants (e, f, g, h) under various scenarios.

Table 4-4. Summary of inputs used for crop production in agricultural lands, concrete road partial depth repair, and lawn sod production.

Input	**Unit**	**Quantity**	**Data Source**
Crop production in agricultural lands			
Land-use change	ha	-	Values are different for different scenarios and different decontamination options
Planting	ha	-	
Combine harvesting	ha	-	
Application of plant protection	ha	-	
Ammonia fertilizer	kg/ha	240	Gençer et al. (2020)

Table 4-4 (continued). Summary of inputs used for crop production in agricultural lands, concrete road partial depth repair, and lawn sod production.

Input	**Unit**	**Quantity**	**Data Source**
Concrete road partial depth repair			
Epoxy resin	kg/m^2	0.29	Jung et al. (2008)
Concrete	kg/m^3	147	Calculated based on thickness of spall and adhesive thickness
Diesel requirement for diamond blade saw	L/m^2	0.7	Diesel requirement for a 49 HP diamond blade saw working for 3.6 minutes
Diesel requirement for sandblaster	L/m^2	0.8	Diesel requirement for a sandblaster with a 3/8" air compressor nozzle working at 100 psi for 3.6 minutes
Transportation distance of the concrete to the site	km	9	Göswein et al. (2018)
Production of lawn sod			
Grass seeds	kg/ha	200	Smetana and Crittenden (2014)
Lime fertilizer	ton/ha	1	Smetana and Crittenden (2014)
Ammonia	kg/ha	147	Trenholm et al. (2010), Landschoot (2017)
Water for irrigation	m^3/ha	381	Smetana and Crittenden (2014)
Frequency of watering	times/yr	36	Smetana and Crittenden (2014)
Mowing requirement by a motor mower	times/yr	27	Smetana and Crittenden (2014)
Sod weight	ton/ha	250	Smetana and Crittenden (2014)
Transportation distance of grass seeds to the sod farm via single-unit diesel truck	km	50	Smetana and Crittenden (2014)
Transportation distance of the sod to the site via single-unit diesel truck	km	50	Smetana and Crittenden (2014)

4.2.4 Impact Assessment

In this study, SimaPro (PRé-Sustainability 2019) software has been used for performing the LCA, and Impact 2002+ (Humbert et al. 2012) has been used for assessing the environmental impact. SimaPro is a science-based tool where it can calculate the environmental impact caused throughout the life-cycle of a product, process, or system provided that the materials and energy requirements are entered as the inputs. Several impact assessment approaches are available within the SimaPro database, any of which can be used to assess the environmental impact. Impact 2002+ (Humbert et al. 2012) methodology is a midpoint damage-oriented approach where midpoint indicators characterize the impact caused on human health, ecosystem quality, climate change, and resources. The impact measured by the midpoint indicators of these four damage categories are combined to represent the respective damages in DALY (Disability-Adjusted Life Years), PDF-m^2-y (Potentially Disappeared Fraction of species over a certain area for a certain duration), kg of CO_2 and MJ (megajoules). The higher the values, the higher the imposed impact on the damage categories. DALY characterizes severity of the disease, and accounts for both mortality and morbidity. For example, a product or a system having a human health damage score of 5 DALY implies that the product or the system is responsible for loss of five years of life over the overall population. PDF-m^2-y characterizes the impact on ecosystems, for example, a product or a system having an ecosystem quality damage score of 0.1 PDF-m^2-y implies that the product or the system is responsible for 10% loss of species over 1 m^2 area during a year. In contrast, a product or a system having a climate change damage score of certain kg of CO_2 and a resources damage score of certain MJ imply that the product or the system is responsible respectively for that amount of CO_2 emission and that amount of energy extraction.

To represent the overall impact caused, the measured damages in their respective units are normalized by the average impact in that damage category caused by a person in Europe in one year. The human health average damage is 0.0071 DALY/point, the ecosystem quality average damage is 13,800 PDF-m^2-y/point, the climate change average damage is 9,950 kg of CO_2/point, and the resources average damage is 152,000 MJ/point (Humbert et al. 2012).

4.3 Results and Discussion

To analyze the results, environmental impacts were determined from the SimaPro output. Table 4-5 represents the environmental impacts caused for decontamination using hydrants and a containment pond with hydrants. It is observed that using a containment pond can readily reduce the environmental impacts on all types of damage categories for the studied scenarios. Table 4-6 depicts the normalized environmental impacts determined from the SimaPro output to compare the overall results on the same scale. It is seen that Scenario 2, i.e., urban road scenario had the highest environmental impact among all the scenarios. A containment pond with hydrants reduced the environmental impacts by 25% in the rural scenario, 69% in the urban roads scenario, 51% in the urban lawn scenario, and 64% in the combined scenario (Table 4-7). Additionally, the individual scenarios were compared with the combined scenario i.e., partly urban, partly rural scenario to note the effect of the type of land exposed to contaminated water discharge (Table 4-8). It is seen that if the area surrounding the hydrants are completely rural lands or lawns rather than combined, the environmental impact can be less by 68-86% for conventional hydrant flushing and 57-71% for containment pond and hydrant flushing. However, the environmental impact can be 240% more in the case of hydrant discharge on to concrete roads and 193% more in the case of containment pond and hydrant discharge on to concrete roads. Since among all the scenarios, urban roads scenario had the maximum environmental impact (Table 4-7), it showed more environmental impact when compared to combined scenario.

Table 4-5. Environmental impacts of different WDS decontamination options at various scenarios.

Damage Category	**Scenario 1: Rural lands**		**Scenario 2: Urban Roads**		**Scenario 3: Urban Lawns**		**Scenario 4: Partly Rural, Partly Urban**	
	Hydrant Flushing	Containment Pond & Hydrant Flushing	Hydrant Flushing	Containment Pond & Hydrant Flushing	Hydrant Flushing	Containment Pond & Hydrant Flushing	Hydrant Flushing	Containment Pond & Hydrant Flushing
Human Health (DALY)	0.783	0.593	13.6	4.32	1.62	0.839	4.19	1.61
Ecosystem Quality (PDF-m^2-y)	$2.99x10^5$	$2.13x10^5$	$2.82x10^6$	$9.48x10^5$	$1.06x10^6$	$4.36x10^5$	$1.12x10^6$	$4.58x10^5$
Climate Change (kg of CO_2)	$7.54x10^5$	$5.62x10^5$	$3.34x10^7$	$1.01x10^7$	$1.92x10^6$	$9.03x10^5$	$9.22x10^6$	$3.09x10^6$
Resources (MJ)	$1.49x10^7$	$1.14x10^7$	$3.23x10^8$	$1.01x10^8$	$3.29x10^7$	$1.67x10^7$	$9.63x10^7$	$3.57x10^7$

Table 4-6. Normalized environmental impacts of different WDS decontamination options at various scenarios.

Damage Category (Points)	**Scenario 1: Rural lands**		**Scenario 2: Urban Roads**		**Scenario 3: Urban Lawns**		**Scenario 4: Partly Rural, Partly Urban**	
	Hydrant Flushing	Containment Pond & Hydrant Flushing	Hydrant Flushing	Containment Pond & Hydrant Flushing	Hydrant Flushing	Containment Pond & Hydrant Flushing	Hydrant Flushing	Containment Pond & Hydrant Flushing
Human Health	110	83.7	$1.91x10^3$	610	229	118	591	227
Ecosystem Quality	21.8	15.5	206	69.2	77.4	31.8	81.7	33.5

Table 4-6 (continued). Normalized environmental impacts of different WDS decontamination options at various scenarios.

Damage Category (Points)	**Scenario 1: Rural lands**		**Scenario 2: Urban Roads**		**Scenario 3: Urban Lawns**		**Scenario 4: Partly Rural, Partly Urban**	
	Hydrant Flushing	Containment Pond & Hydrant Flushing	Hydrant Flushing	Containment Pond & Hydrant Flushing	Hydrant Flushing	Containment Pond & Hydrant Flushing	Hydrant Flushing	Containment Pond & Hydrant Flushing
Climate Change	76.2	56.8	$3.38x10^3$	$1.02x10^3$	194	91.2	931	312
Resources	97.8	74.9	$2.12x10^3$	666	216	110	634	235
Total	306	231	$7.62x10^3$	$2.37x10^3$	716	351	$2.24x10^3$	808

Table 4-7. Reduction in environmental impacts (%) over the conventional flushing method by using a containment pond and hydrant flushing.

Scenario	**Percent Reduction**
Scenario 1: Rural lands	25
Scenario 2: Urban Roads	69
Scenario 3: Urban Lawns	51
Scenario 4: Partly Rural, Partly Urban	64

Table 4-8. Comparison of the individual scenarios with the Partly Rural, Partly Urban scenario.

Scenario	**Percent Reduction in Environmental Impact**	
	Hydrant Flushing	Containment Pond and Hydrant Flushing
Scenario 1: Rural lands	86	71
Scenario 2: Urban Roads	-240	-193
Scenario 3: Urban Lawns	68	57

A sensitivity analysis was also performed to observe the resulting changes in overall GHG emissions for changing the key variables to the two decontamination options. Each of the key variables was increased and decreased by 10% while keeping the other variables the same as the base case and the change in GHG emission from the base case was recorded (Figure 4-3 and Figure 4-4). Emissions for the time of decontamination in Scenario 1, the area of land exposed to contaminated water in Scenario 2, and the area of land exposed to contaminated water (hydrant flushing alone) and the decontamination time (containment pond and hydrant flushing) in Scenario 3 had the largest impact on their respective overall results. By contrast, emissions for pond construction and fertilizer usage in Scenarios 1 and 3 were very small, and the emissions for the change in pond construction in Scenario 2 was negligible.

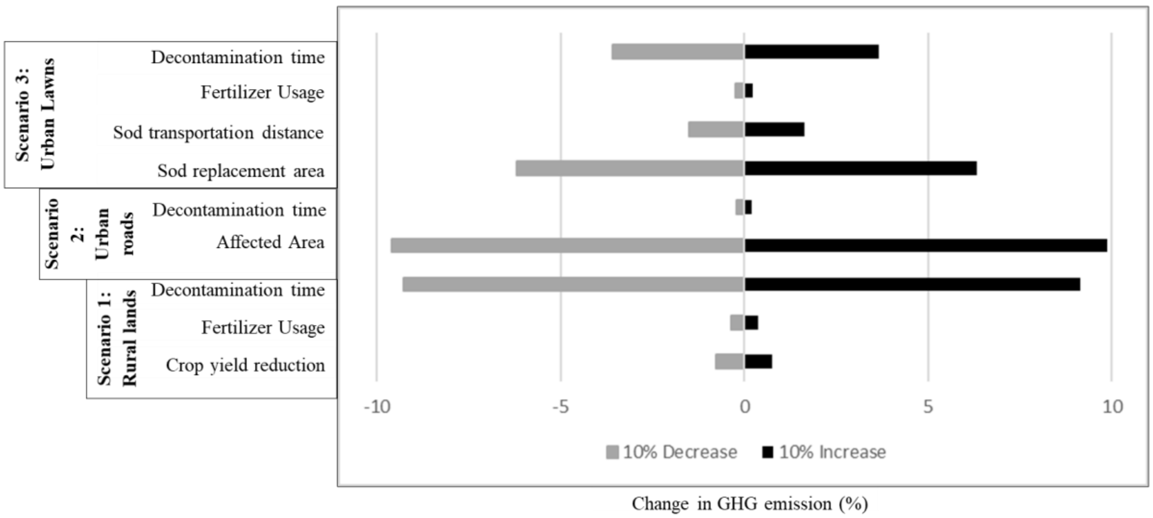

Figure 4-3. Sensitivity analysis for key inputs to hydrant flushing at various scenarios.

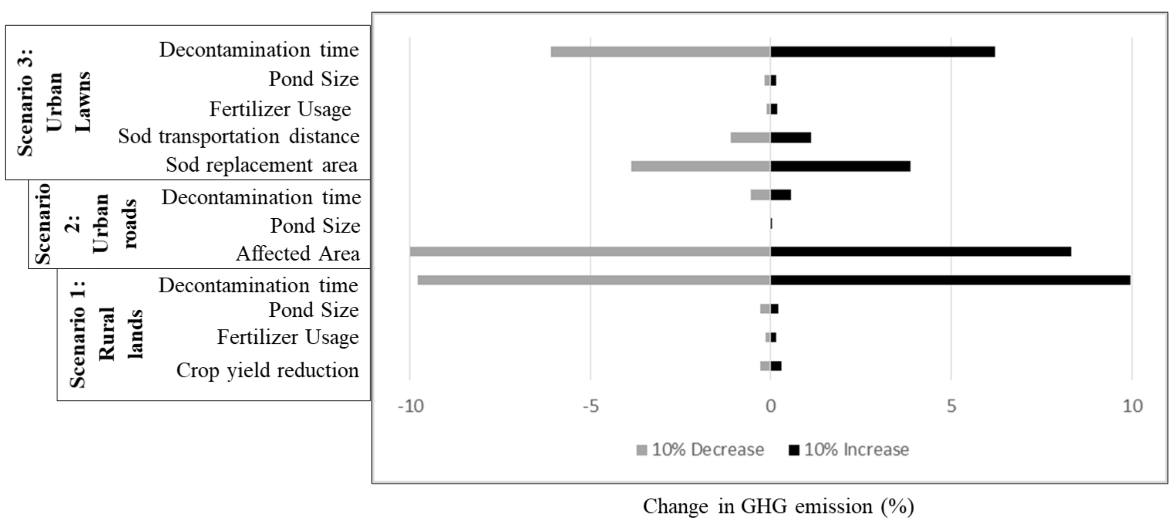

Figure 4-4. Sensitivity analysis for key inputs to containment pond and hydrant flushing at various scenarios.

4.4 Conclusions

This study was conducted to compare the decontamination of a WDS using fire hydrants and a containment pond in terms of environmental impacts. To achieve that goal, a life cycle assessment was performed on the decontamination options. The following points can be concluded from the outcome:

1. For WDS decontamination, using a containment pond can reduce environmental impact compared to hydrant flushing alone irrespective of the type of surroundings around the WDS.
2. Contaminated water discharge to concrete roads can be more harmful from an environmental viewpoint if the type of contaminant is detrimental to concrete service-life.
3. Use of a containment pond in addition to hydrants can be more effective in an urban area since the study found that the use of a containment pond with hydrants in urban areas reduced the environmental impact by more than 50% for the assumptions made.
4. Decontamination of a WDS situated around agricultural lands or lawns can impose a comparatively less environmental footprint rather than a WDS situated in a combined environment.
5. The time needed for the WDS decontamination, and the area of land exposed to contaminated water discharge are the most sensitive variables to environmental impact for the studied decontamination procedures.

5 Concluding Remarks

This research was conducted to document different types of systems' behavior with salt intrusion at the reservoir/s at different rates, to explore an alternative to hydrant flushing for a contamination event, and to compare the decontamination of a WDS using fire hydrants and a containment pond in terms of environmental impacts. The major findings of the research are as follows:

- If salt enters a system as a short pulse, it may move around the system and contaminate different parts at different times, even though the rest of the system will become clean.
- In a multi-reservoir system, if any reservoir remains fresh during a salt contamination event, contamination might take a longer time to reach all edges of the system and the salt spread will not be the same.
- For any type of system, the time to clear the system from salt contamination will be linearly correlated to the rate of salt entry at the source.
- Using a containment pond for WDS flushing can be a better option than hydrant flushing from an environmental perspective.
- The containment pond might not be able to clear areas of the distribution system away from the pond.
- For some systems, the best location of the containment pond might vary 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.
- For WDS decontamination, using a containment pond can reduce environmental impact compared to hydrant flushing alone irrespective of the type of surroundings around the WDS.
- The use of a containment pond in addition to hydrants can be more effective in an urban area.
- The time needed for the WDS decontamination, and the area of land exposed to contaminated water discharge are the most sensitive variables to environmental impact for the studied decontamination procedures.

Some ideas which can be explored further based on this study are:

- Describing a WDS based on its topology to find a relation with the salt spread.
- Applying Lagrangian Method (Shang et al. 2021) to compare the resulted changes in salt spread by considering dispersion transport mode.
- Developing a new system with optimal containment pond location to recommend the best way of system flushing.
- Studying adaptation to salt-water intrusion which may include changing the water source/s, incorporating desalination, etc.
- Studying contaminants other than salt for a containment pond.
- Studying the social perspective, along with economic and environmental perspectives for a decontamination procedure.

- Studying actual uncertainty in the input variables of the decontamination procedures.

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A Supplementary Figures for Chapter 3

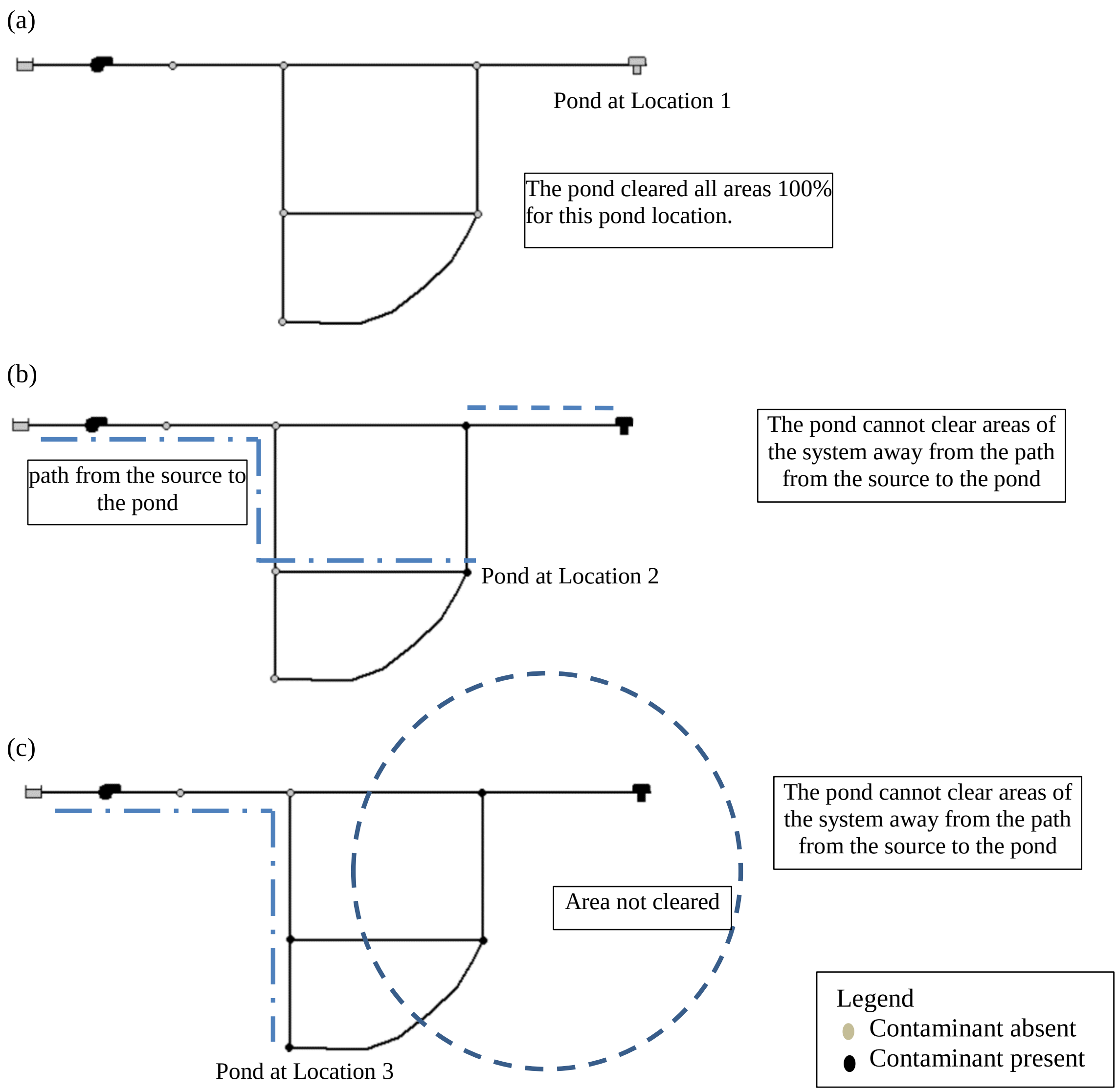

Figure A.1. System A at pond maximum capacity for the pond at (a) Pond Location 1, (b) Pond Location 2, and (c) Pond Location 3. The same thing holds for the other systems as seen in Table 3-3.

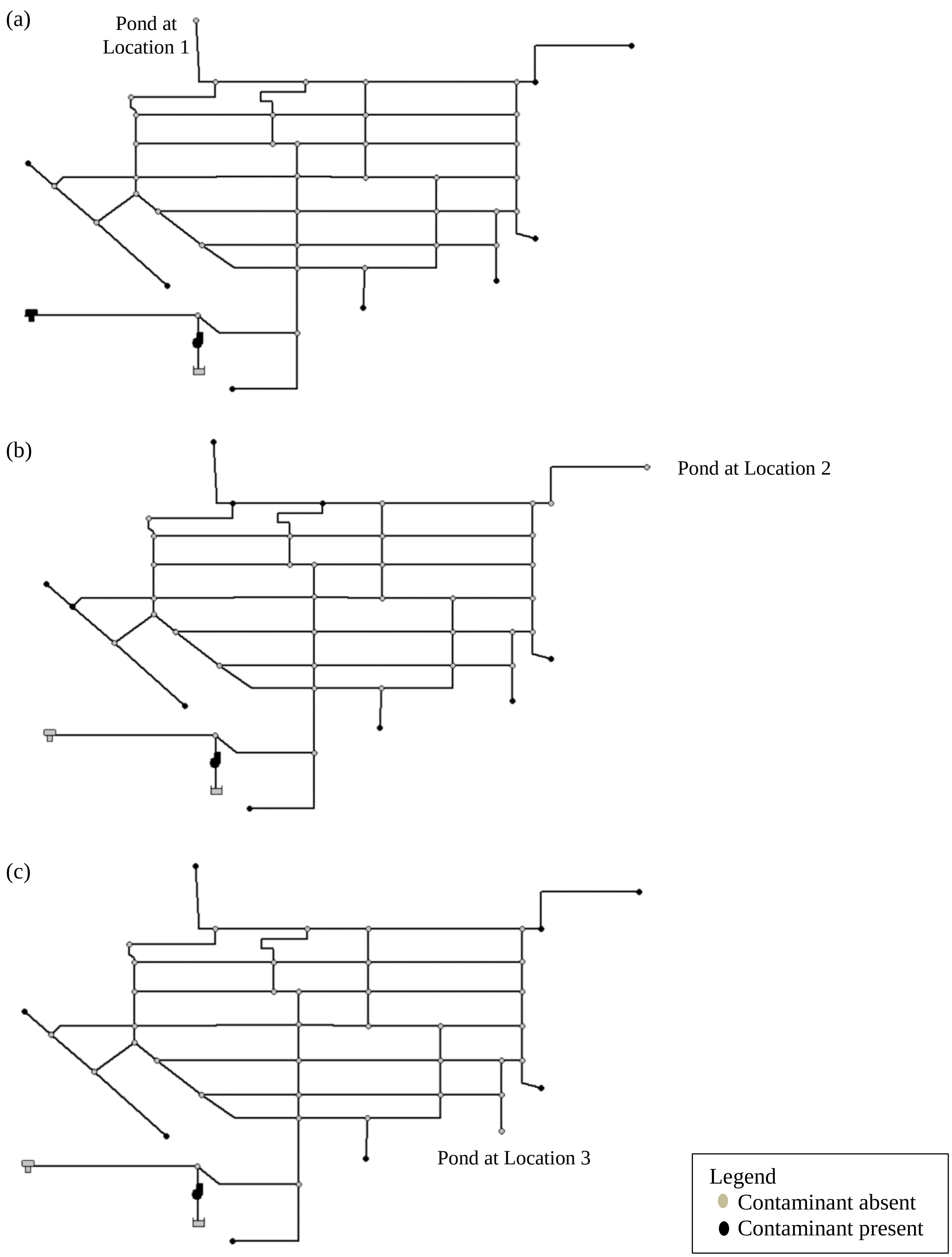

Figure A.2. System B at pond maximum capacity for the pond at (a) Pond Location 1, (b) Pond Location 2 and (c) Pond Location 3.

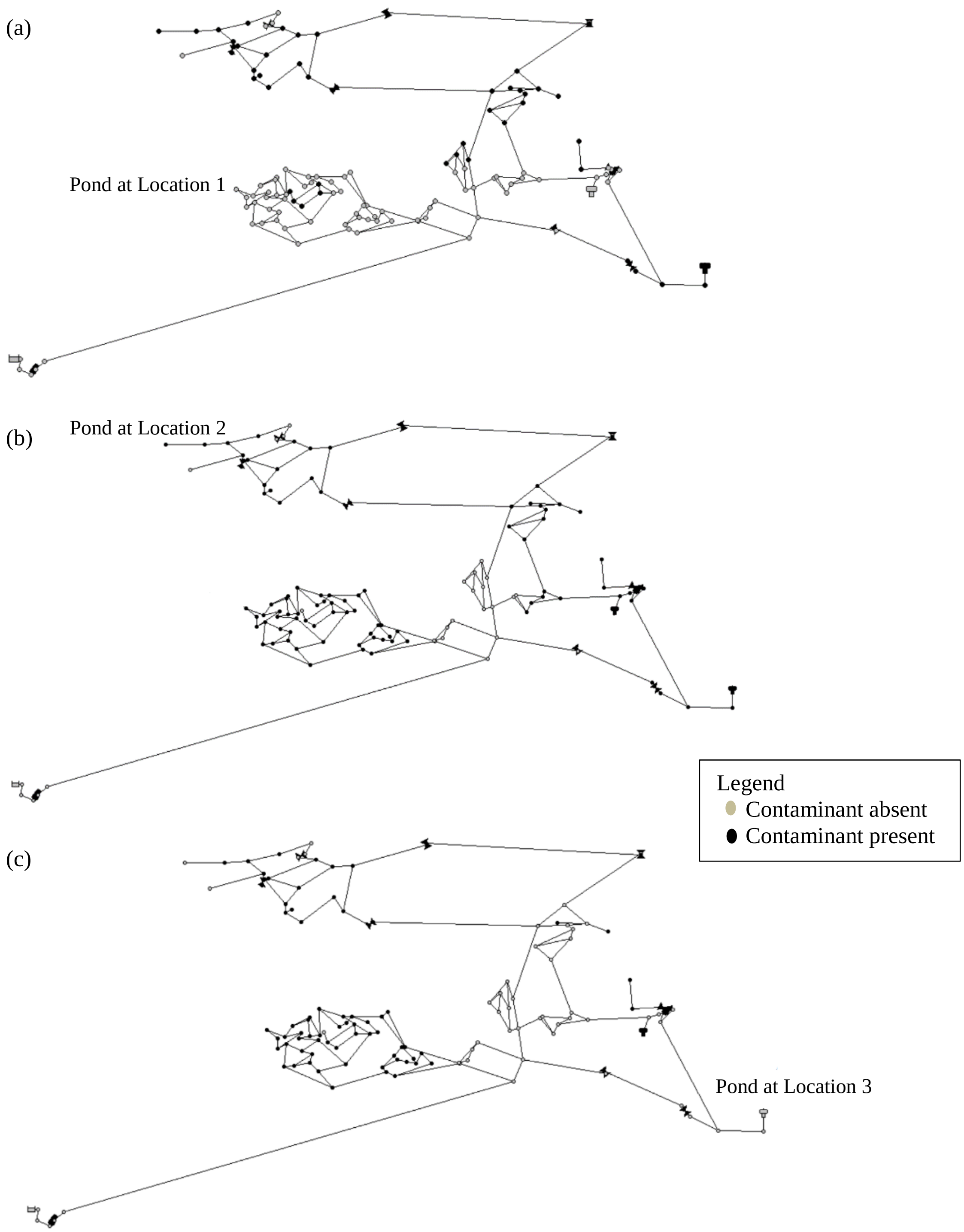

Figure A.3. System C at pond maximum capacity for the pond at (a) Pond Location 1, (b) Pond Location 2 and (c) Pond Location 3.

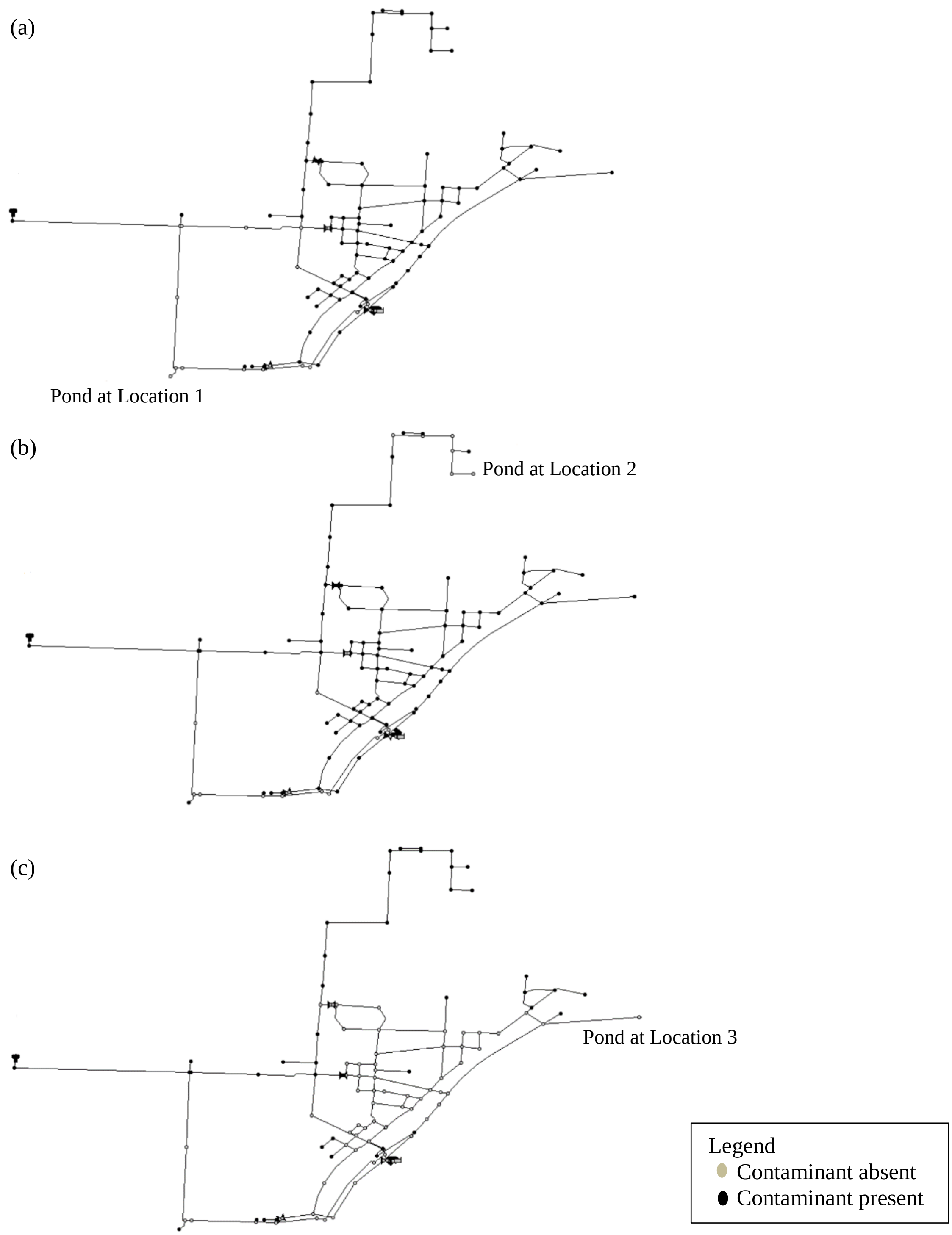

Figure A.4. System D at pond maximum capacity for the pond at (a) Pond Location 1, (b) Pond Location 2 and (c) Pond Location 3.

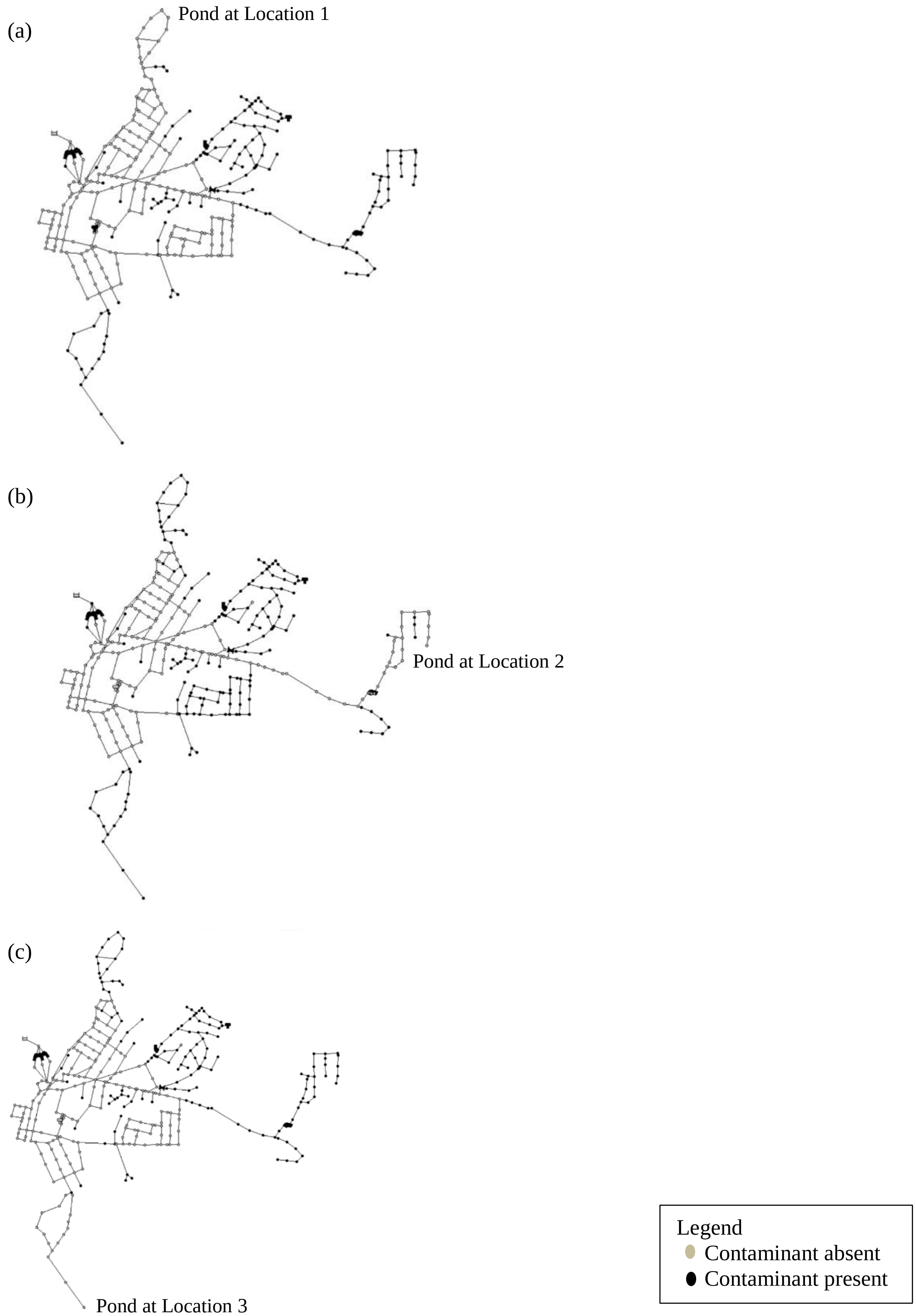

Figure A.5. System E at pond maximum capacity for the pond at (a) Pond Location 1, (b) Pond Location 2 and (c) Pond Location 3.

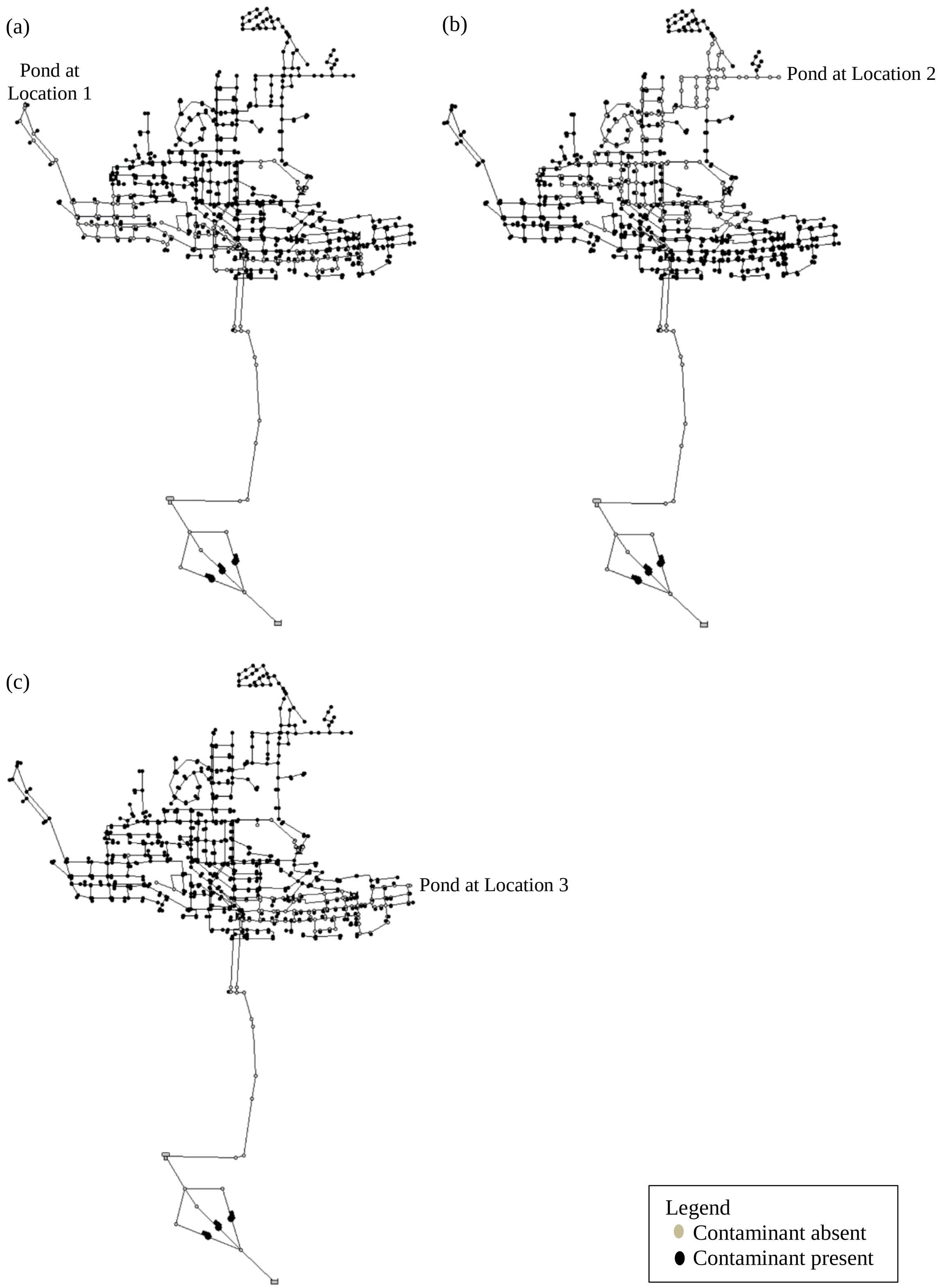

Figure A.6. System F at pond maximum capacity for the pond at (a) Pond Location 1, (b) Pond Location 2 and (c) Pond Location 3.

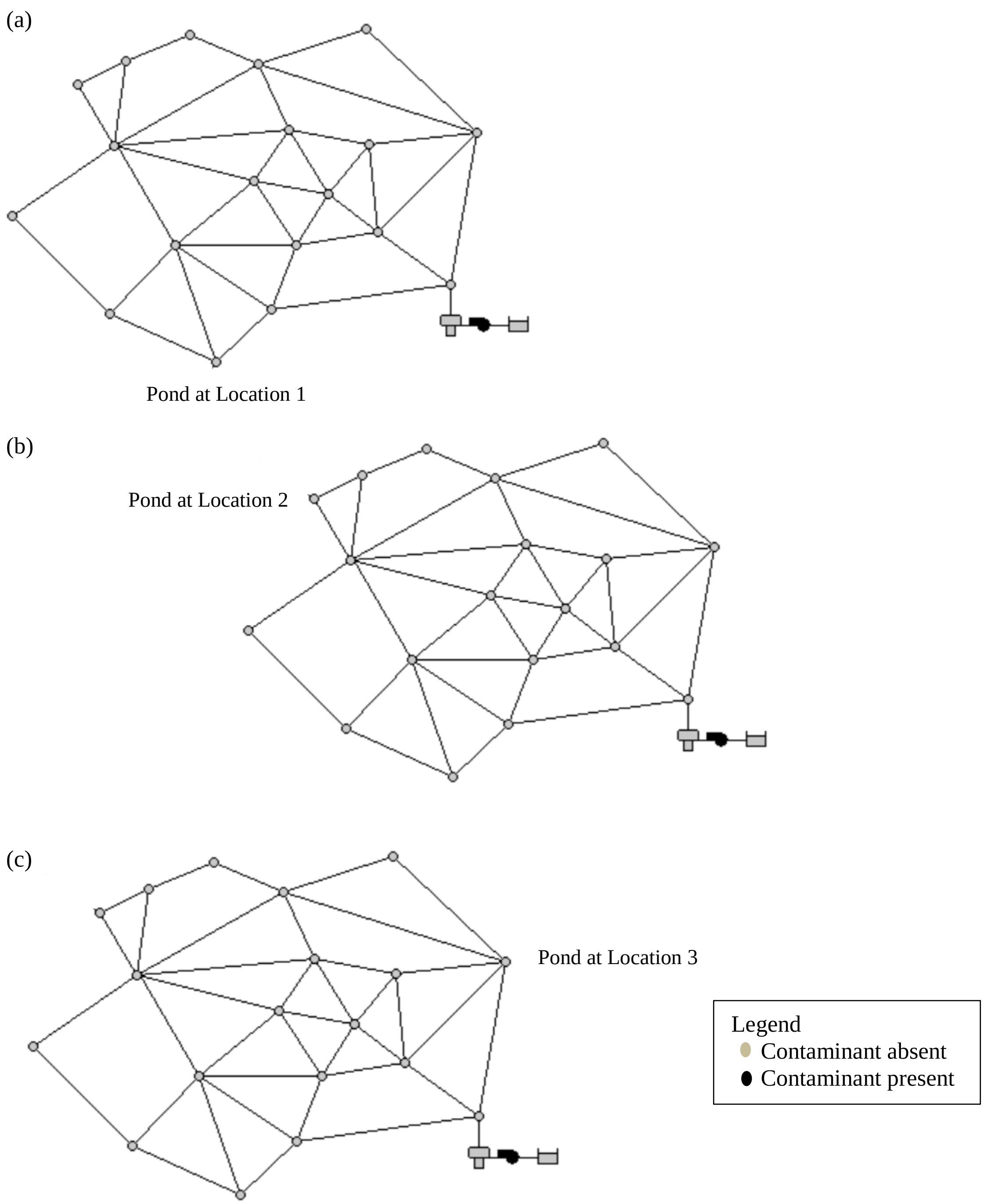

Figure A.7. System G at pond maximum capacity for the pond at (a) Pond Location 1, (b) Pond Location 2 and (c) Pond Location 3.

Figure A.8. System H at pond maximum capacity for the pond at (a) Pond Location 1, (b) Pond Location 2 and (c) Pond Location 3.

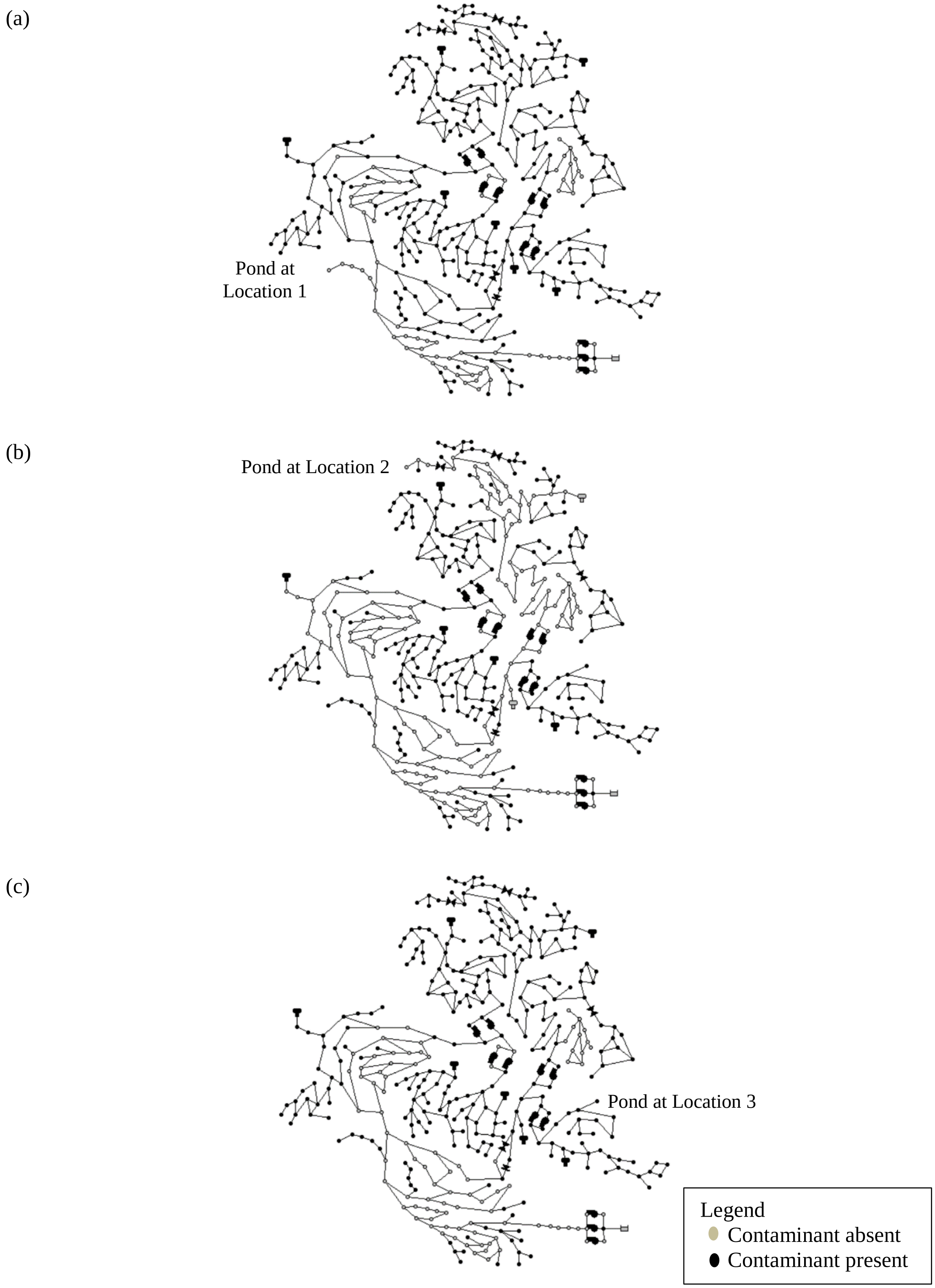

Figure A.9. System I at pond maximum capacity for the pond at (a) Pond Location 1, (b) Pond Location 2 and (c) Pond Location 3.