Contamination and Clean-up of a Potable Water Supply System: A Simulation Modeling Approach

Final Report

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Executive Summary

The main objective of this study was to evaluate the impacts of intentional or accidental contamination of a potable water supply system for a typical town in the U.S. Southwest. Different decontamination options were also explored. EPANET, a water supply system simulation model, was used to evaluate contamination and decontamination scenarios. Three types of contaminants were evaluated including (i) inorganic contaminants, (ii) biological contaminants, and (iii) organic toxins.

The following questions were explored: (1) How is the spread of contaminant in the water supply system influenced by the location where the contaminant is introduction? (2) How does a contaminant move through the system under different scenarios when a system has water supply from multiple sources? (3) How does the contaminant spread in the water system when different concentrations of contaminant are introduced in the water supply system? and (4) What are the clean-up times and volume of contaminated water generated in different clean-up scenarios?

Results indicate that system demand and the location of the contaminant with respect to the source feed appear to dictate how far and how fast a contaminant will propagate through the system. Contamination at or closer to the water source impacts larger portions of water system compared to contamination at neighborhood locations. Multiple sources of water supply tend to limit the area of water supply system that will be contaminated compared to a single water supply source.

Sensitivity analysis on the relationship between the contaminant's initial concentration and the contaminated volume shows that there is a threshold concentration and that a contaminant need not be introduced at its maximum soluble concentration in order to be harmful.

Estimates of clean-up time and volume of contaminated water show that the minimal time required (6 hours) and minimum volume of water (2.35 million gallons (Mgal)) contaminated would occur when both taps and fire hydrants are operated. This strategy of opening both taps and hydrants is feasible for contaminants that pose a threat only when water is ingested. If a contaminant is too dangerous to be discharged into a user's home, then flushing through the fire hydrant may present less risk. Decontamination takes 7 hours and generates less contaminated water (1.89 Mgal). Opening taps is less effective (more time consuming) than opening fire hydrants to flush the system.

Based on the results of this study, the following recommendations are made.

- Although general conclusions can be drawn, every water system is unique and should be modeled individually. Water utilities that already have a water system model should modify that model to include contaminant transport. Towns that do not have a water distribution model can use existing drawings of the system layout and water demands to create a model. They can use a similar approach used in this study to understand how water moves in their system and which sources and neighborhood locations are critical. They can evaluate potential actions to be taken in case a contamination incident occurs.

- Water utilities should pay special attention to protecting the water sources (reservoirs, storage tanks), especially the tanks that are located upstream and feed the largest portion of the system.

- Even though contaminating a neighborhood location is less critical, water utilities should pay attention to protecting neighborhood locations that feed hospitals or schools.

- Although the amount of contaminant required to contaminate a larger water system may be difficult to obtain and deploy, small water utilities should not underestimate the potential to contaminate a system because, for most highly toxic chemicals, only a small amount of contaminant is required. If a contaminant is introduced to a neighborhood location using a truck mounted pump the system could be contaminated in a short duration.

- Water utilities should avoid feeding the entire system from one storage tank. Instead multiple smaller tanks should be considered.

- Because of higher flow rates and location, fire hydrants should be used to flush contaminated systems rather than opening taps in homes.

- Water utilities should estimate the volume of water that will be contaminated. With this estimate they should evaluate if their sewer system and storm water system will be able to handle the contaminated volume flushed through fire hydrants. If not, provisions should be made to build temporary storage (e.g. ponds).

- If water is contaminated with a compound that would affect the operation of a waste water treatment plant (e.g. compounds that are toxic to bacteria), then contaminated water would have to be transported by trucks to storage ponds where it could be treated. Even for a small system the number of tuck loads required is very large.

- The U.S. Environmental Protection Agency (EPA) has compiled a list of potential contaminants for water systems. Water utilities should select inorganic, organic and biological contaminants from that list with low contaminant thresholds and run models to prepare for worst case contamination scenarios.

- Water utilities should determine the amount of disinfectant required to clean up the system. This amount is what they would need to procure in a timely manner in case of an incident.

- Water utilities should explore the possibility of decontaminating the system by pH (measure of the acidity or alkalinity of a solution) changes; there are several inorganic contaminants that are less toxic at different pH levels.

- Water utilities should identify the locations (e.g. storage tank or fire hydrant) in the water system where disinfectants or decontaminating compounds should be added to provide for effective clean-up.

1. Introduction and Objectives

In the United States more than 160,000 public water systems provide drinking water to more than 300 million Americans. In addition to providing potable drinking water, these water systems are critical to the maintenance of many vital public services, such as fire suppression and power generation. The threat of intentional contamination of water supplies is not new. In 1941, the Director of the Federal Bureau of Investigation J. Edgar Hoover acknowledged the vulnerability of the U.S. water supply to an attack:

> *It has long been recognized that among the public utilities, water supply facilities offer a particularly vulnerable point of attack to the foreign agent, due to the strategic position they occupy in keeping the wheels of industry turning and in preserving the health and morale of the American Populace.*
> (Copeland and Cody, 2005)

In 1996, the nation's water supply was designated as one of eight national infrastructure sectors vital to the security of the United States, through the issuance of Executive Order (EO) 13010. EO 13010 established the President's Commission on Critical Infrastructure Protection, which concluded in 1997 that there was inadequate protection against chemical or biological contamination of water supplies. Improving the security of our nation's drinking water and wastewater infrastructures has become a top priority since the events of September 11th, 2001 (Nuzzo, 2006).

Water system modeling: A water system model can help in making better decisions when responding to an emergency, whether it is an accidental spill or an intentional act. Models of water distribution systems can estimate the concentration of a chemical or biological contaminant at any point in the system at any time. These models can be a valuable tool in deciding how to respond to a contamination event. Additionally, running a water simulation model can show where the contaminant would travel if active measures to control its spread are not taken. This can give a baseline of how critical a situation can become if no action is taken to redress the situation.

Modeling should not be reserved for real-time emergencies. In fact, modeling can best be used in planning for emergencies before they occur. Simulating emergencies in water systems can help identify weaknesses and thus better prepare for actual contamination events. Running a model for a water system can be a valuable part of emergency planning policies and procedures.

Evaluating clean-up options: Estimating the effects of clean-up actions without a simulation model is basically an exercise in judgment. The problem is complicated further by the fact that water movement in a distribution system is fairly non-intuitive and system specific. Water does not move smoothly through the system but tends to slosh back and forth with variation in user consumption and as pumps are turned on and off.

Modeling informs decision making: Modeling flows through the water system assists in predicting the effects of potential clean-up actions. Developing water simulation models take time, depending on the complexity of the system and the availability of data. Developing and calibrating a water system model may take weeks and even months. Though computer tools such as computer-aided design (CAD) drawings or Geographic Information Systems (GIS) can reduce the model development time, but models cannot be built during a crisis event.

Today, most large water utilities have some sort of hydraulic pipe network model of their water distribution system; however, many are only steady state models. These are good for water distribution system analysis and design, but not useful for tracking water quality, which is a dynamic process. Extended-period simulation (EPS) models are needed as a starting point for contamination analysis. These models describe the hydraulics of the system over time. To build a water quality model from an EPS model, information concerning the source of the contaminant being modeled and information on how the contaminant travels through the pipes is required. With this information, the effects of clean-up measures to be taken, in case of a contamination incident, may be evaluated. The first step is to use the model to determine where the contaminant is likely to spread. The model can then be used to evaluate the impacts of alternative clean-up measures. Once the location of contaminant is known and the effects of alternative clean-up measures have been predicted, the clean-up team can be directed appropriately. They can open hydrants to move the contaminant out of the system and operate pumps and valves to keep it from spreading within the system. Therefore, computer models of water systems can be valuable tools to guide decisions regarding the clean-up of contamination events.

Objectives of Study

The main objective of this study is to investigate various contamination scenarios for a potable water supply system and explore various clean-up (de-contamination) options. The water supply system for a section of a town, representing a typical southwestern U.S. town, is modeled using water network analysis software, EPANET.

Water utilities can use a similar approach to develop a model for their water systems and evaluate potential actions to be taken in case a contamination incident occurs. To demonstrate the development and application of a water system model, some example questions are explored in this study. Water utilities, using a water network analysis model, can analyze their water system based on similar questions.

The following questions are explored in this research:

1. How is the spread of a contaminant in the water supply system influenced by the location where contaminant is introduced?
2. How does a contaminant move through the system under different scenarios when the system is supplied water from multiple sources?
3. How does a contaminant spread in the water system when different concentrations of contaminant are introduced in the water supply system?
4. What are the clean-up times and volume of contaminated water generated in different clean-up scenarios?

Scope of proposed work: Drinking water could be contaminated at the water source (e.g., a lake or reservoir), during treatment, in storage tanks, or in pipes that distribute water to points of use. Water systems could be compromised through biological, chemical, or radiological contamination or through physical damage to the treatment or supply of water. Water supplies could also be disrupted through cyber attacks on computer systems that control delivery and treatment, or through interruption of transportation of chemical disinfectants or electricity for pumping. Although this vast range of possibilities should be considered when evaluating threats to a water supply system, this study will focus on the possibility of a biological/chemical contamination of a water supply system.

2. Modeling Approach

Computer modeling of the water distribution system was performed using EPANET 2.0. EPANET is a water network analysis tool developed by the US Environmental Protection Agency and it is available free for public use (http://www.epa.gov/nrmrl/wswrd/dw/epanet.html). Analysis capabilities include steady as well as varied demand flow scenarios to show a daily variation in the demand patterns. EPANET is also capable of analyzing the path of travel and transformation of any single contaminant introduced in the water network.

2.1 Model Study Area

To demonstrate how a water utility could develop a model for their water supply system and evaluate clean-up options once a contamination incident occurs, a model is developed for a section of a typical town in the southwestern region of the U.S. The total area of this section is one square mile (640 Acres). The area of study is shown in Figure 1.

Besides EPANET, there are other commercially available software packages to model water distribution systems. If towns already have a water system distribution model, it can be modified to address questions regarding contamination. Towns that do not have a water distribution model can use existing drawings of the system layout and water demands to create a model in EPANET or any other modeling tool. After the model has been created and calibrated, knowledge on the fate and transport of contaminants can be incorporated to determine the extent of contamination.

Land Use and Water Demand. The land use for this analysis is selected to match the typical layout of commercial, single-family homes, apartments/condos, parks, and school areas. There are multiple possible configurations regarding distribution of land uses. Therefore the selected distribution is a random arrangement without any specific reference to a particular municipality. Table 1 shows the percentage of total area for each land use within the study area.

Table 1 – Land use distribution in study area

Land Use	% of Total Area
Medium Density Residential	24%
Residential	52%
Low Density Residential	6%
Commercial	11%
Parks and Recreation	4%
Schools	3%

Once the analysis area is populated with different land uses, water demands can be calculated for each land use type. Water demands used in this analysis are typical for the desert southwest, where water demands are higher than in many other locations due to higher temperatures. Each land use has a demand factor either based on number of dwelling units or acreage, whichever yields a higher demand value. For example, the average day demand for a single family neighborhood is either 0.52 gallons per minute (gpm)/housing unit or 2.3 gpm/acre. If the number of units exceeds 4.7 units per acre, then the demand per unit factor will yield a higher demand value than the demand per acre factor. Areas labeled as "Residential" have a density of 8 units per acre; areas labeled as "Medium Density Residential" have 18 units per acre; and areas labeled as "Low Density Residential" have 2 units per acre. In the case of the "Low Density Residential," it is more conservative to use the demand per acre calculation than the per unit demand calculation. Table 2 shows the factors used to calculate demand for all of the land uses.

Table 2 – Water Demand Calculations

User Description	Flow Rate	
	Gallon per minute/ unit	Gallon per minute/acre
Single Family Residential	0.52	2.3
Apartments, Condominiums and Townhouses	0.21	5.7
Golf Courses, Parks, and Open Spaces	-	4.4
Commercial	-	2.1
Schools	-	1.7

Pipe Network. Once the water demands are calculated, the pipes can be added to the computer model. The pipes for the system were overlaid on the land use distribution as shown in Figure 1. There are two classes of pipes shown, transmission pipelines and distribution pipelines. The former category includes pipes 16-inches and larger (thicker lines shown in Figure 1) while the latter category covers pipes 14-inches and smaller (thinner lines shown in Figure 1). The transmission lines are placed along what represents the major roadways of the suburban areas. In survey terms, they are located along the section lines (the boundary of the suburban section) and the half section lines (the east-west and north-south bisectors of the section). The transmission pipelines range in sizes from 16-inches to 24-inches. All other pipelines (i.e. not located along the section or half section lines) are the distribution lines and range in sizes from 8-inches to 12-inches. The total length of pipe is 64,807 feet, or 12.2 miles. Within the computer model each pipe starts and ends at a 'junction point' (shown as numbers in Figure 1). Each junction point represents a place where water may enter or exit the system. The demands calculated in previous step are applied as positive demand values at the junctions to represent water leaving the system. For the system under study the average daily demand is 6,867 gallons per minute (gpm).

For an existing water system, the pipe sizes and demands are known and this information could be used by water utilities to develop the model using the approach described above.

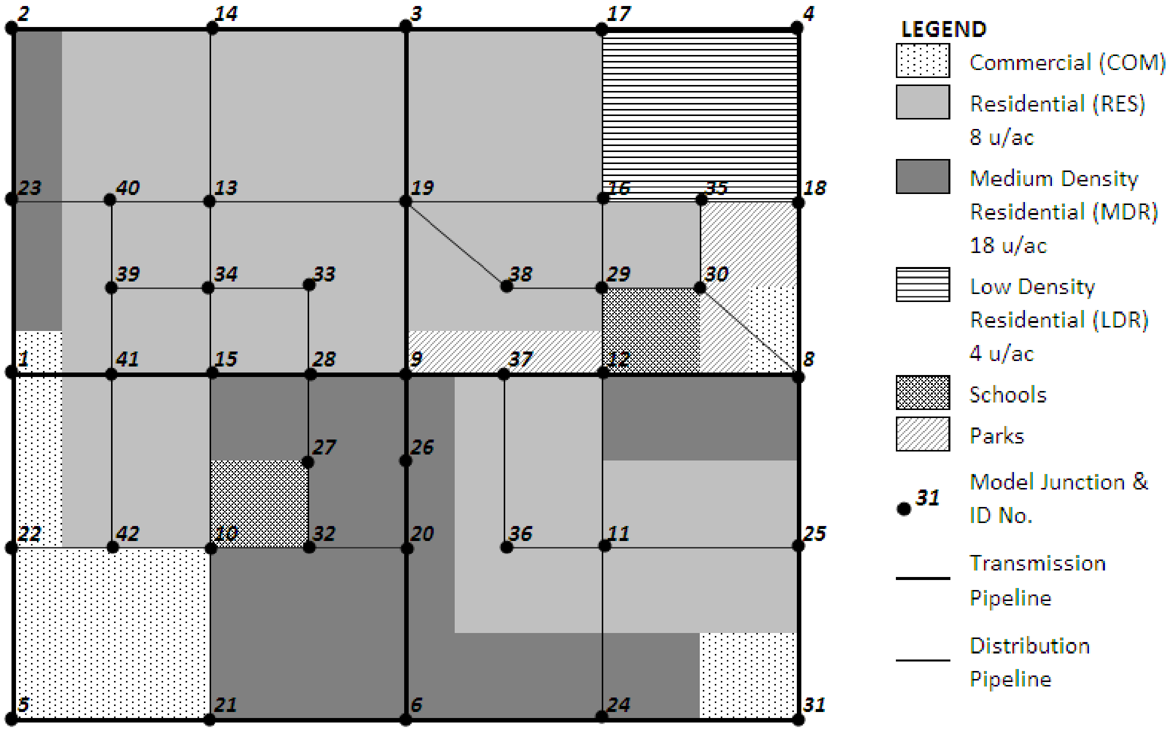

Figure 1. Example water distribution network and land use in the study area

Water Sources. A typical small town may supply its water system with a pump filling a single storage tank. However, within most large communities there is redundancy built into the system, which takes the form of multiple pumps and storage tanks servicing different areas. For the example evaluated here, the pumps and storage tanks were modeled as water sources in this study. For this analysis, three different water sources were considered, which can be opened separately or in combination with each other to evaluate contaminant propagation within the system. Figure 2 shows the location of three water sources numbered 1-3. For a specific water system, existing water tanks have to be added to the model. In addition, hypothetical water tanks could be added to explore the effects of additional tanks on the spread of contaminant and in responding to a contamination incident.

Model Verification. Prior to starting the contamination and clean up scenarios for the water system, the model was verified to assure there is adequate residual pressure at each model junction and that the flow velocities do not exceed the maximum permissible velocity. For the network in question, the minimum allowable residual pressure was chosen as 40 pounds per square inch (psi). After completing a residual pressure analysis the minimum pressure observed in the system was found to be 40.30 psi. The maximum flow velocity in the pipes was determined to be 4.74 feet/second.

2.3 Potential Contaminants to Water Systems

Water distribution systems are composed of a network of storage tanks, pipes, valves, and fire hydrants. These systems are pressurized and operated under different pressure zones, depending on the system layout. Intentional contamination of these systems would require introducing contaminants to storage tanks or pumping contaminants into the network of pressurized pipes and valves. The numbers of materials that can be used to intentionally contaminate potable water system is very large and include organic and inorganic chemicals, biological agents, and radiological materials (Burrows and Renner, 1999 and Field, 2004).

The viability of such intentional contamination is dependent upon the layout of the distribution system, the availability of bulk amounts of the contaminant, and the size of the distribution system to be contaminated. Furthermore, introduction of these compounds would require equipment to transport the contaminants and introduce them into a pressurized pipe or valve. While the contamination of large water systems would require sizable amounts of these materials, the contamination of a small system or portion of a large system is possible with smaller quantities.

In addition to influencing the spread of contamination, the layout of the distribution system also influences the rate of decontamination efforts. If contaminants are introduced to large storage tanks, the only viable clean-up alternative may include flushing the contaminant through the network of pipes. If contaminants are introduced into pressured pipes, valves, or fire hydrants, flushing the pipes with fresh water or a neutralizing chemical may be a possible alternative. Clean-up procedures must include provisions for flushing the distribution system and treatment and disposal of the contaminated water generated in the flushing. If a model has been developed for the system, it may be possible to isolate uncontaminated portions of the system to minimize the volume of water that has to be treated and/or discharged.

For the section of the city evaluated in this study, contamination spread and clean-up was evaluated for three types of contaminants:

- Inorganic Contaminant: the inorganic contaminant under consideration is highly soluble in water, causes acute toxicity to humans and animals, and has a very low lethal concentration. This compound’s toxicity can be decreased by increasing the pH of the water. Therefore, modeling of decontamination involved the introduction of sodium hydroxide (NaOH) to the distribution system to reach a desired pH at which the compound is less toxic.
- Biological Contaminant: the biological agent is easily carried by water and it can be inactivated by common disinfectants such as sodium hypochlorite or chlorine dioxide. The disinfectant dosage needed to perform decontamination considered the decay of the disinfectant concentration as it travels the pipe system and a minimal disinfectant residual needed at the point of water delivery.
- Organic Toxin: the organic toxin is very soluble in water with an extremely low lethal dosage, about 100,000 times smaller than that of the inorganic contaminant considered. Similar to biological agents, this toxin responds to inactivation by disinfectants.

Typically the fate of a contaminant is evaluated by combining the advective movement of the contaminant with its decay rate constants. For example, if a system were to be chlorinated, EPANET allows for the estimation of the desired chlorine residual in the system by using a rate equation for the consumption of chlorine as water travels through the pipes.

2.3 Analysis of Contamination Scenarios

Once a water utility has a validated model, various contamination scenarios can be evaluated assuming contaminants are added to storage tanks and the network of pipes.

For the water distribution system evaluated in this study, the first phase of analysis focused on contamination of the water supply system. This analysis aims at answering Questions 1-3 of this research study (See page 6). The main focus here was to determine the spread of a contaminant through the water system considering two scenarios: (1) contamination is introduced directly at one of the water sources, and (2) contamination is introduced directly into pipes at one of the neighborhood locations.

For water source contamination three feed sources (marked as triangles 1-3 in Figure 2) were considered. For 'neighborhood' location contamination, four points were considered (marked as squares 1-4 in Figure 2). The source location can be contaminated by direct input of contaminant into the tank either as a solid or as a concentrated solution. A neighborhood location can be contaminated by directly pumping a contaminant into the water distribution system. For source or neighborhood contamination, the analysis was initiated by pumping 5 gpm of contaminant over a period of 24 hours. For each contamination scenario three water sources were operated either individually or in combination. The contaminant pumping location was also varied to evaluate how the contaminant travels in the system. In addition to location, the concentration of the contaminant was varied to observe the extent of contamination and volume of water contaminated. Once these different scenarios were completed the process was repeated using a higher pumping rate over a shorter period of time.

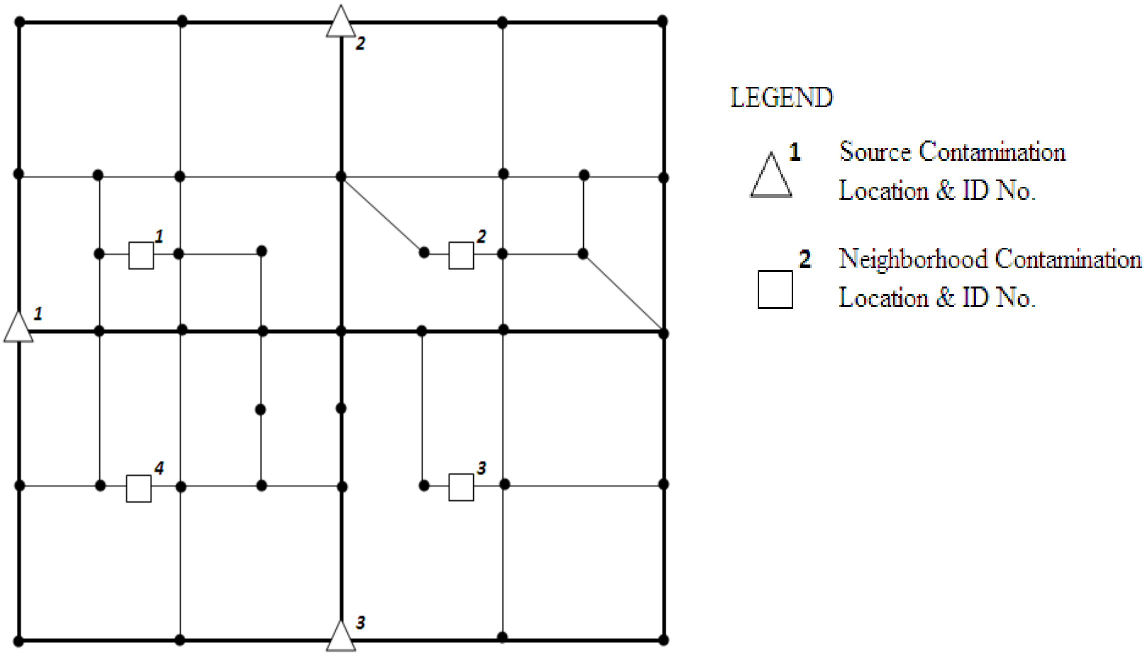

Figure 2. Points of contamination including three sources and four neighborhood locations

2.4 Analysis of Clean-up Scenarios

The second phase of analysis focused on clean-up or decontamination of the water supply system (Question 4). Four contamination/clean-up scenarios were evaluated. In scenario 1, the system is contaminated with an inorganic contaminant and the decision is made to flush-out the system as a clean-up measure. In scenario 2, the system is contaminated with an inorganic contaminant and the decision is made to inactivate this contaminant by increasing the pH of the water. This contaminant is much less toxic to people when the pH of the water is kept high. In scenario 3, the system is contaminated with a biological agent and inactivation is performed using a suitable disinfectant. In scenario 4, the system is contaminated with an organic toxin with extremely low lethal dosage and inactivation of the toxin is possible using disinfectants.

For scenario 1 (i.e., flushing), the worst case (i.e., when entire water system is contaminated) was chosen and clean water was pumped at the same location where the contaminant was introduced. For scenarios 3 and 4 (i.e. the disinfection scenarios), a residual disinfectant analysis was performed to determine the disinfectant consumption rate in the system to maintain a minimum desired residual concentration at all points.

EPANET requires only two distinct inputs to evaluate the fate of the contaminant in the system. These inputs are initial contaminant concentration and decay coefficient. The maximum solubility was used as the initial concentration of the contaminant in question. For inorganic contaminants, initial concentration of 100,000 milligrams per liter (mg/L) was used and then adjusted down to 0.01 mg/L by factors of 10. The decay coefficients for the contaminants were taken from the literature.

Three different flushing alternatives were considered: (i) opening taps, (ii) opening fire hydrants, and (iii) opening both taps and fire hydrants. The rate of flushing was examined when the system was experiencing peak hour demands, so that the demand at each node was increased by a factor of 3.48. The time to remove all traces of the contaminant was computed. With respect to the alternative of opening the taps, the assumption is that all of the residents are instructed to turn on their faucets and showers and allow the contaminant to be discharged into the sewer system for clean up at the local waste water treatment facility. This is possible for contaminants that pose a threat only if water is ingested and can be handled at treatment plant. The alternative of operating the fire hydrant is carried out by turning off the regular demand on the system, and opening up fire hydrants within the system and directing the contaminated water generated to sewer lines or trucks. If a contaminant is too dangerous to be discharged into a user's home, then this scenario may present less risk. For the example study area this scenario assumes that a total of four (4) fire hydrants are opened and are capable of discharging 1,500 gallons per minute of water from the system. The final flushing alternative is performed by using a combination of opening both taps and fire hydrants. The four fire hydrant locations correspond to the four neighborhood contamination location site as shown on Figure 2.

For decontamination procedures, one alternative was considered that involved introducing a disinfectant (e.g., chlorine compound) into the system until desired chlorine residual is reached. The contaminant was introduced at a specified location at its maximum concentration to observe the length of time required to meet the minimum residual criterion in the system. In the analysis presented here we target a chlorine residual concentration of 1 mg/L or 0.001g/L. Under this scenario the chlorine is injected at one of the four fire hydrant location, while the other three are opened to pull the contaminated water out of the system. Similar to the flushing alternatives, the four fire hydrant locations correspond to the four neighborhood contamination location sites as shown on Figure 2.

3. Results and Discussion

3.1 Contamination Spread Results. Figures 3-1 to 3-10 show the extent of contamination when a contaminant is introduced at one source and remaining two sources are either located close to each other or operating in different combinations. Similarly, Figures 3-11 to 3-16 show the extent of contamination when the contaminant is introduced at one of the four neighborhood locations and three water sources are operated in different combinations. These figures represent the contamination of the system by pumping at a rate of 5 gpm for 24 hours. The effects of pumping at much higher (and more realistic) pumping rates over a shorter period of time were also explored.

Interestingly, the same numbers of junctions are contaminated with 5gpm or higher pumping rate. This is because the amount of contaminant needed is very small due to the low toxic threshold levels. This shows that for very toxic compounds it would be relatively easy to contaminate a system using a small pump.

Another finding is that the water system demands have significant influence on how far and how fast the contaminant will propagate. This is because if there is no demand on the system the contaminant will only spread by molecular diffusion.

The location of contamination also influences its spread. Contaminants introduced at water source would spread farther than the contaminants introduced at neighborhood locations. Thus, if a water source is contaminated, then the entire system feeding from that source will also be contaminated. Results also show that the closer a contaminant is introduced to a water source the further the contaminant propagates. This explains why introducing the contaminant at neighborhood locations 2 and 3 had very little impact on the propagation of the contaminant. An additional explanation for this behavior is the direction of flow within the distribution network i.e., water moves from source to point of demand. From this perspective, the further “upstream” a contaminant is introduced the more it will spread “downstream.” Identifying locations where the introduction of contaminant would be critical requires specific knowledge of the distribution system.

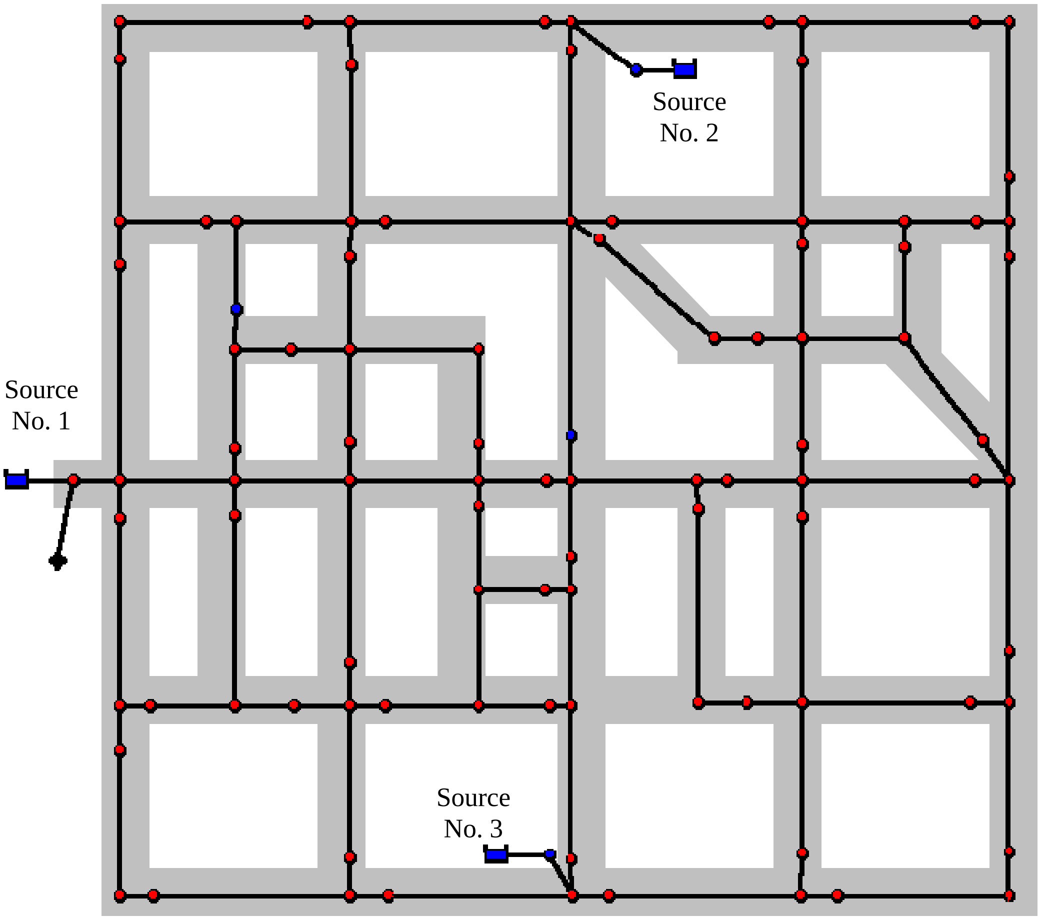

Figure 3-1:
Contaminant at
source No. 1.
Source No. 1 open,
No. 2 & 3 closed.

Note: Shaded areas
denote contaminated
pipelines

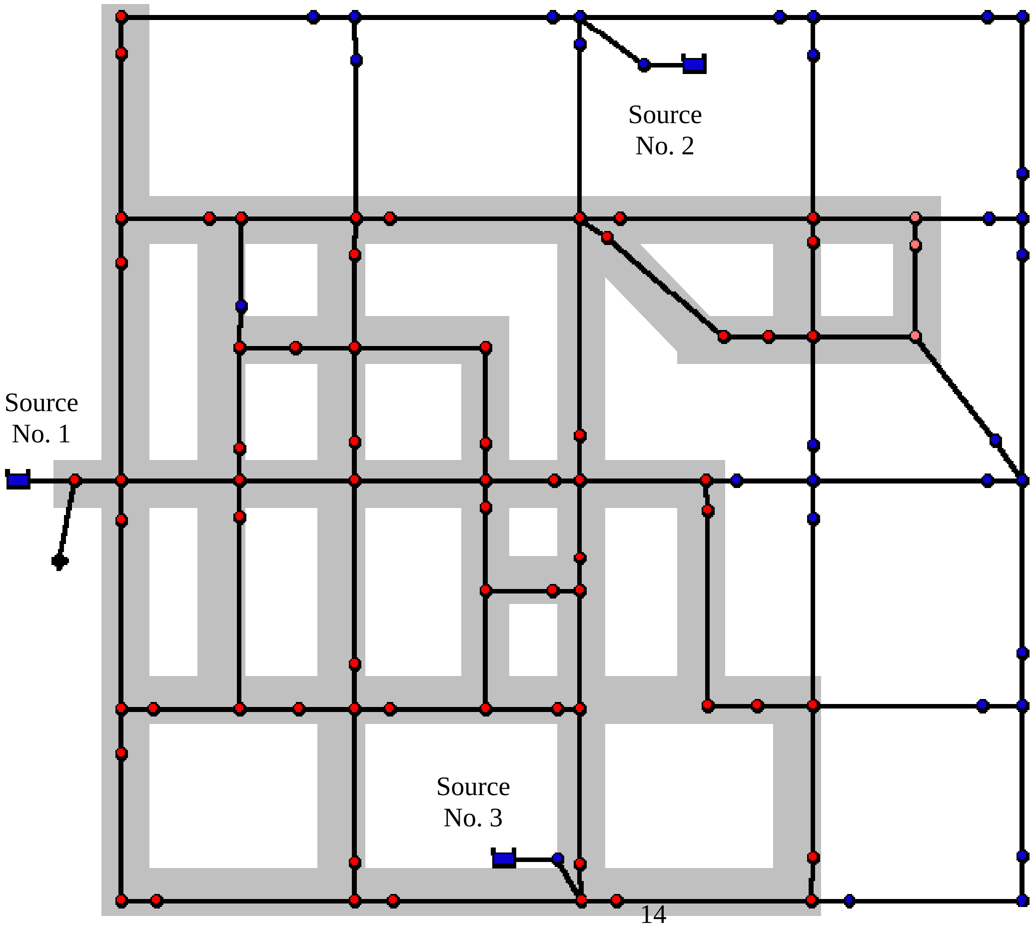

Figure 3-2:
Contaminant at
source No. 1.
Source No. 1 & 2
open, No. 3 closed.

Note: Shaded areas
denote contaminated
pipelines

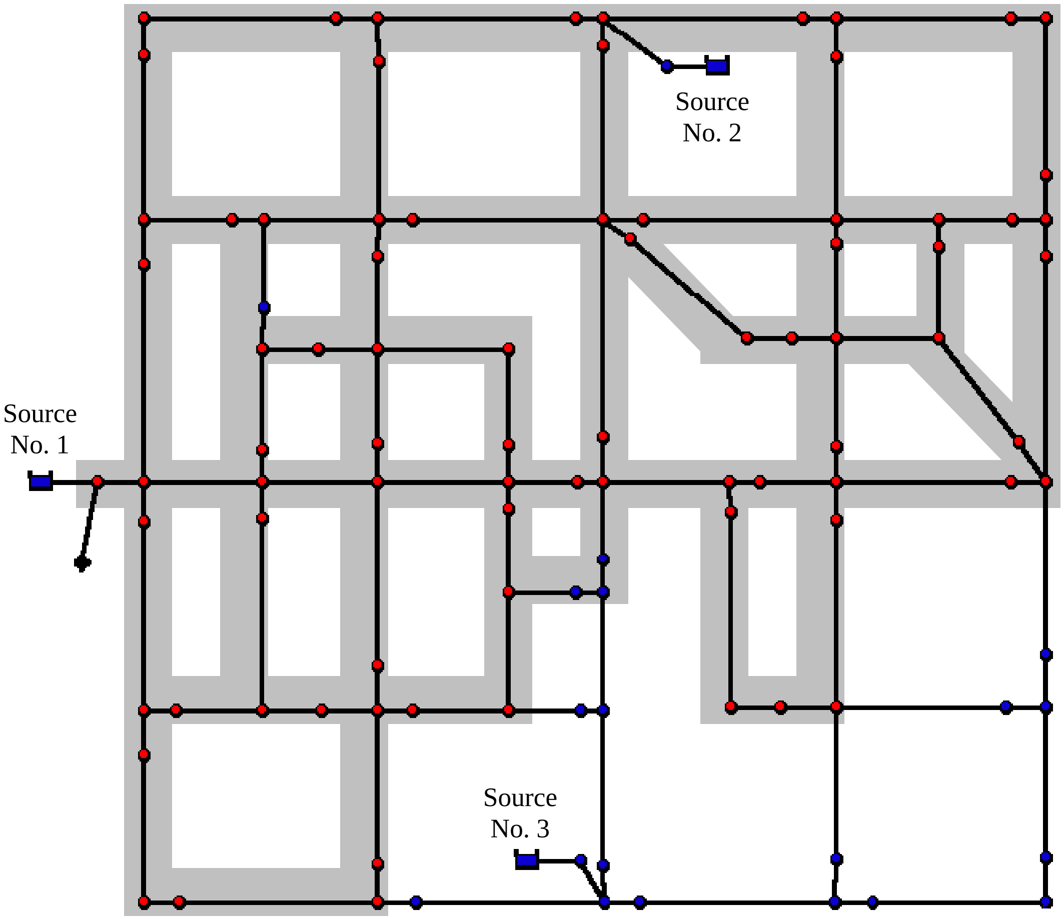

Figure 3-3: Contaminant at source No. 1. Source No. 1 & 3 open, No. 2 closed.

Note: Shaded areas denote contaminated pipelines

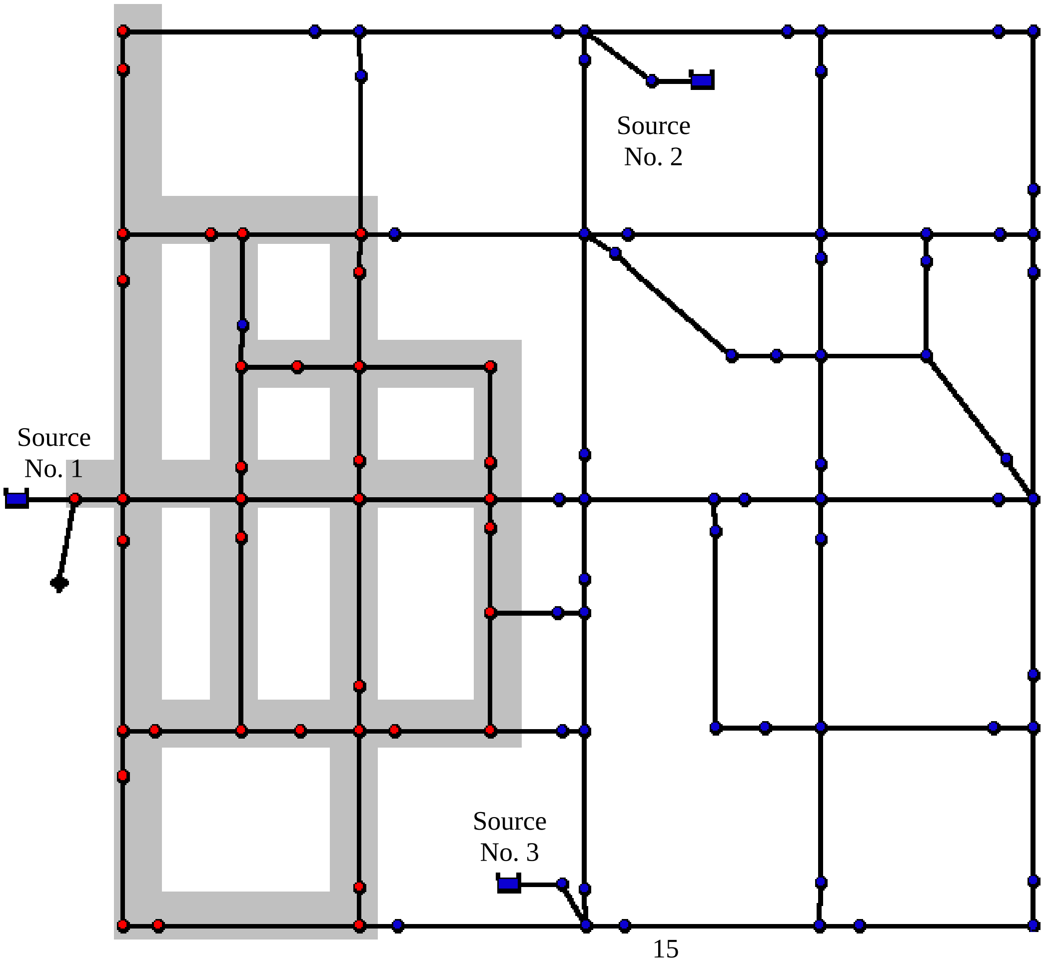

Figure 3-4: Contaminant at source No. 1. All sources open.

Note: Shaded areas denote contaminated pipelines

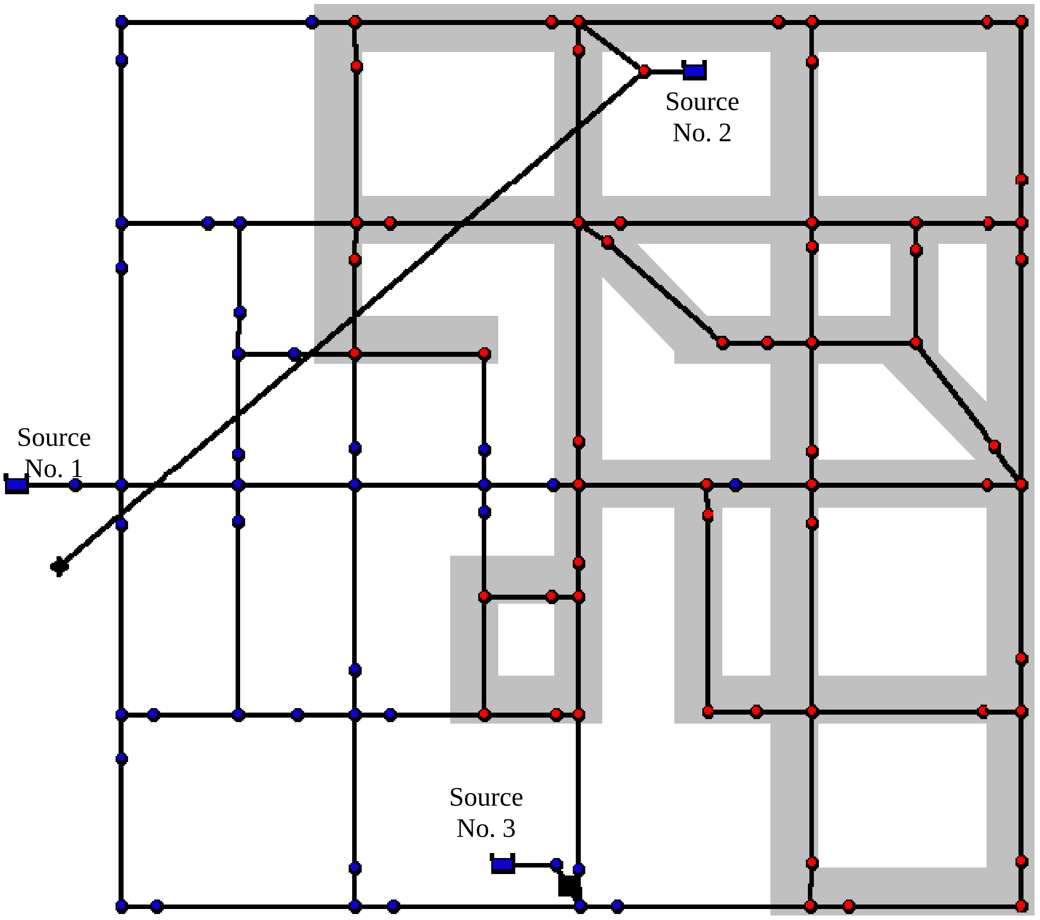

Figure 3-5: Contaminant at source No. 2. Source No. 2 & No. 1 open, No. 3 closed.

Note: Shaded areas denote contaminated pipelines

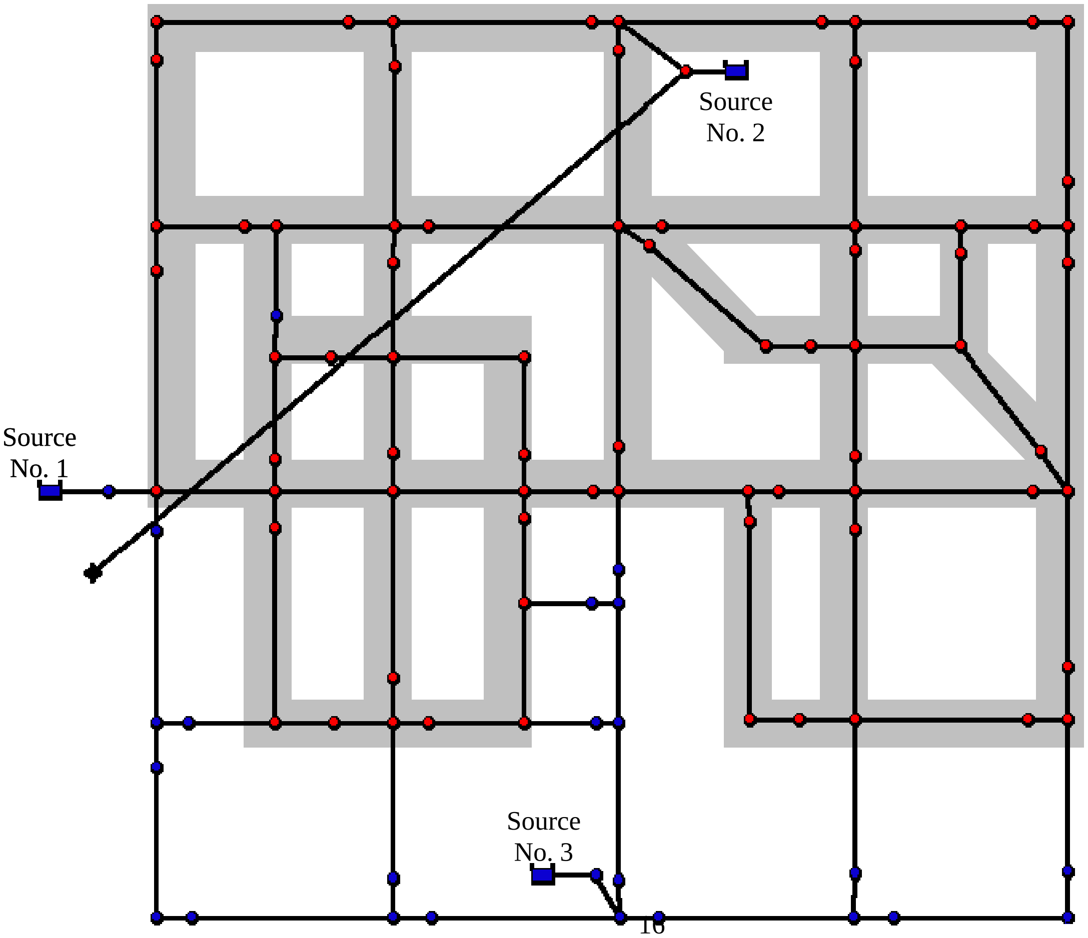

Figure 3-6: Contaminant at source No. 2. Source No. 2 & No 3 open, No. 1 closed.

Note: Shaded areas denote contaminated pipelines

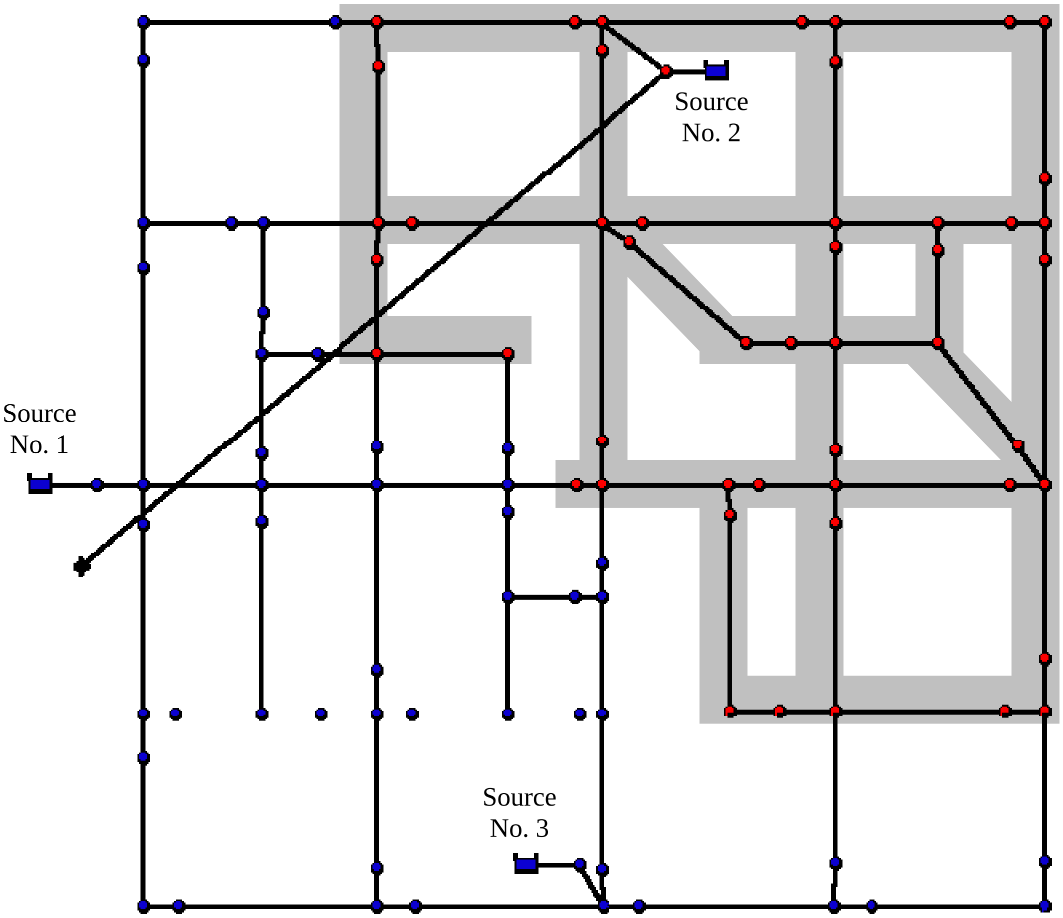

Figure 3-7: Contaminant at source No. 2. All sources open.

Note: Shaded areas denote contaminated pipelines

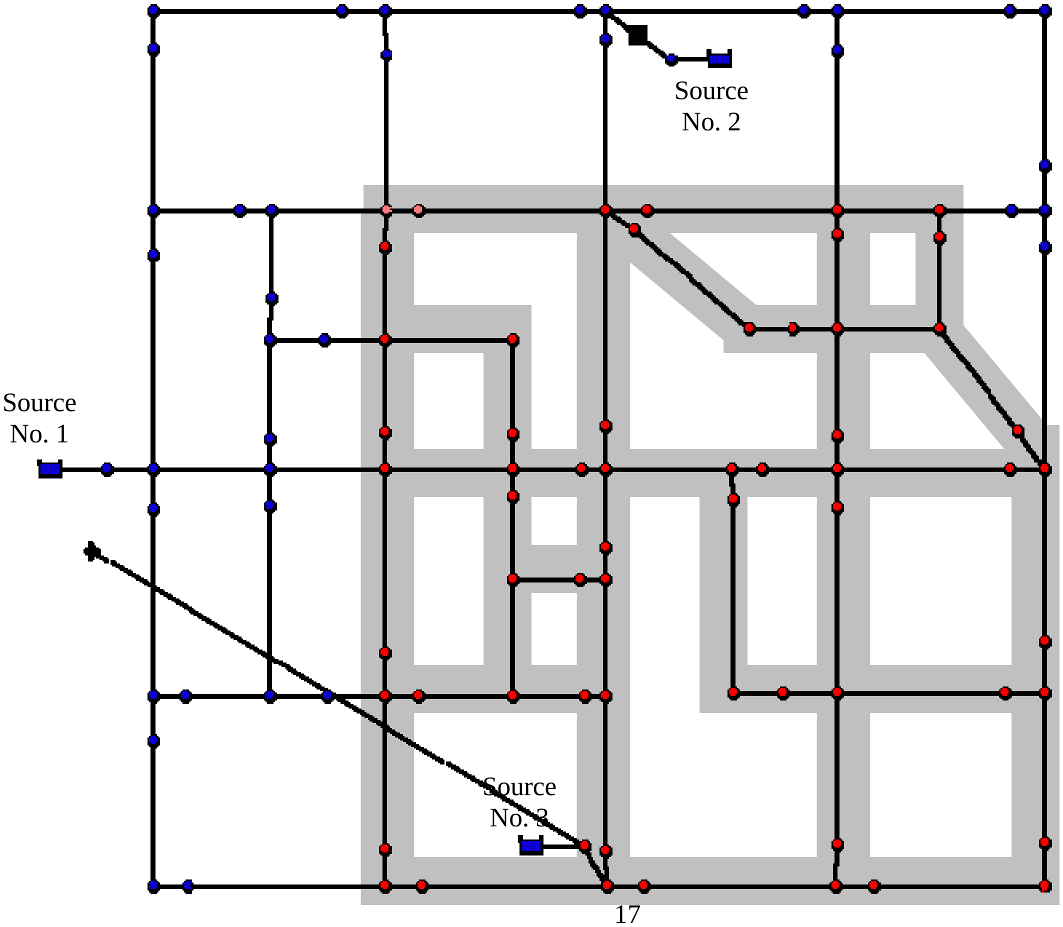

Figure 3-8: Contaminant at source No. 3. Source No. 3 and No. 1 open, with No. 2 closed.

Note: Shaded areas denote contaminated pipelines

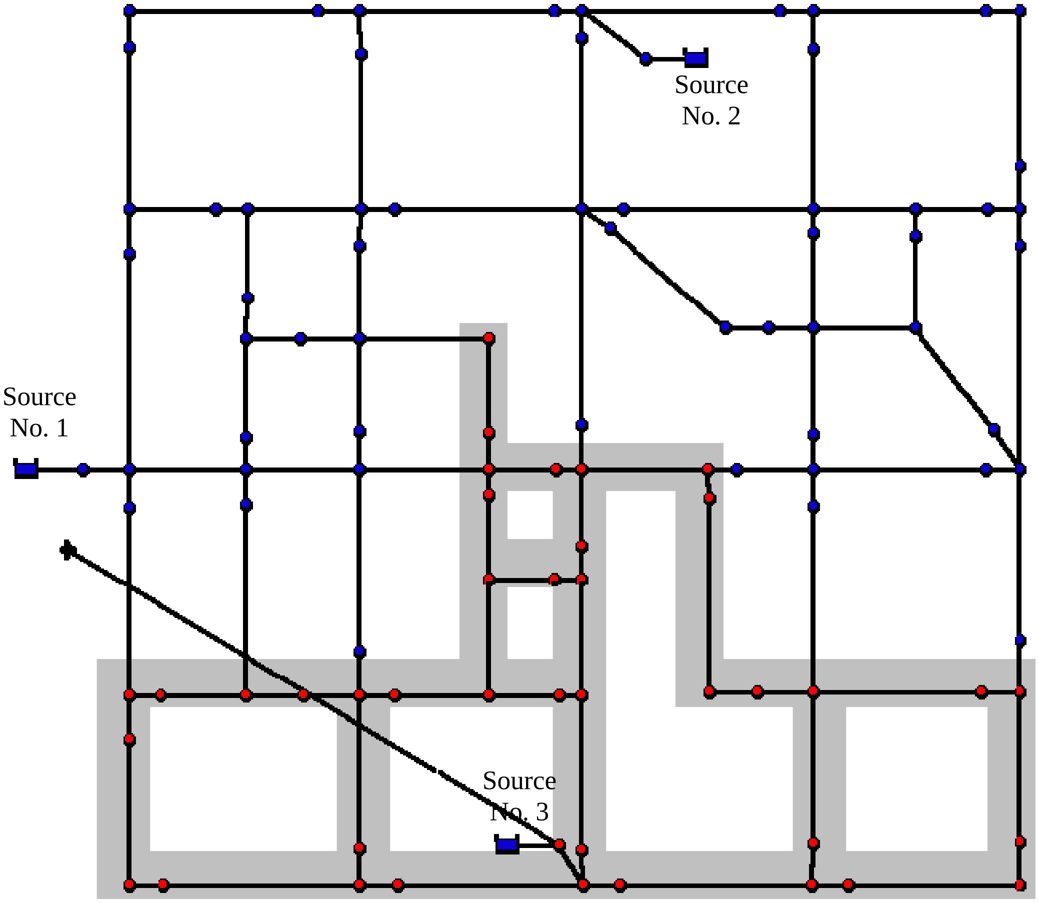

Figure 3-9: Contaminant at source No. 3. Source No. 3 & No. 2 open, No. 1 closed.

Note: Shaded areas denote contaminated pipelines

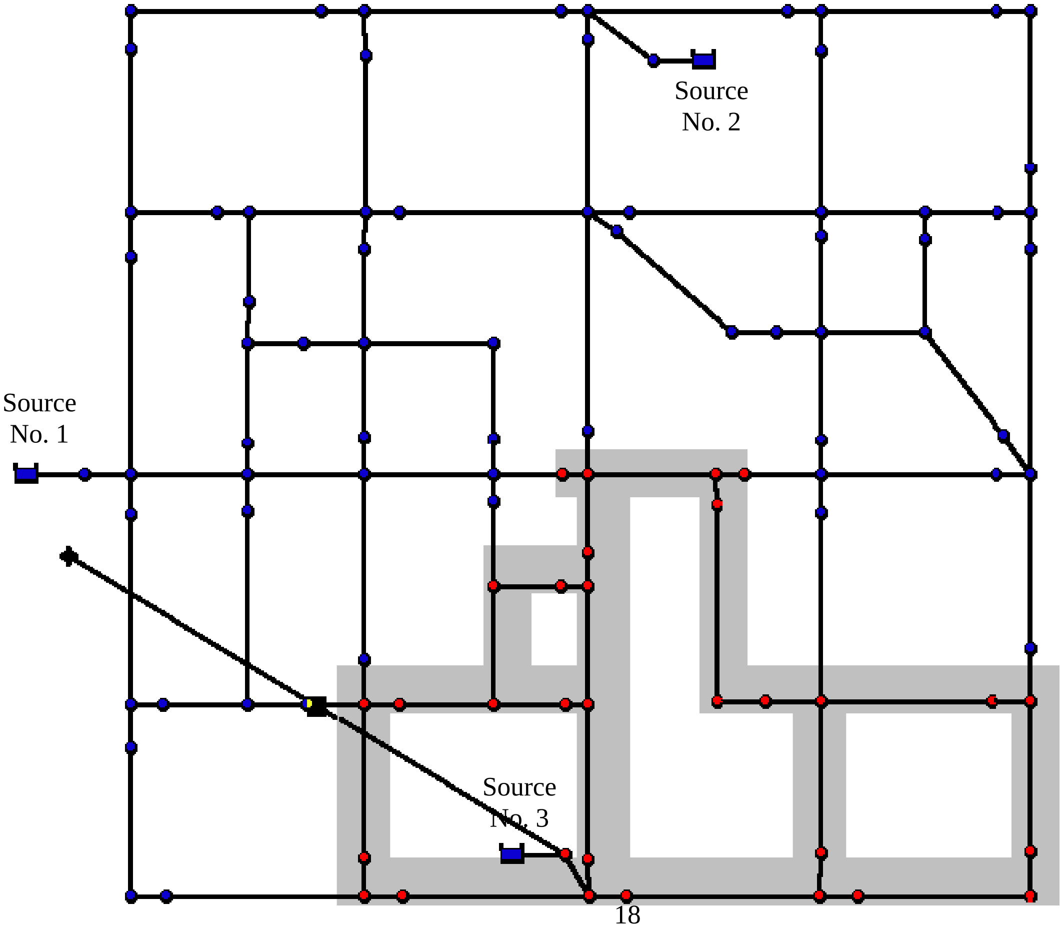

Figure 3-10: Contaminant at source No. 3. All sources open

Note: Shaded areas denote contaminated pipelines

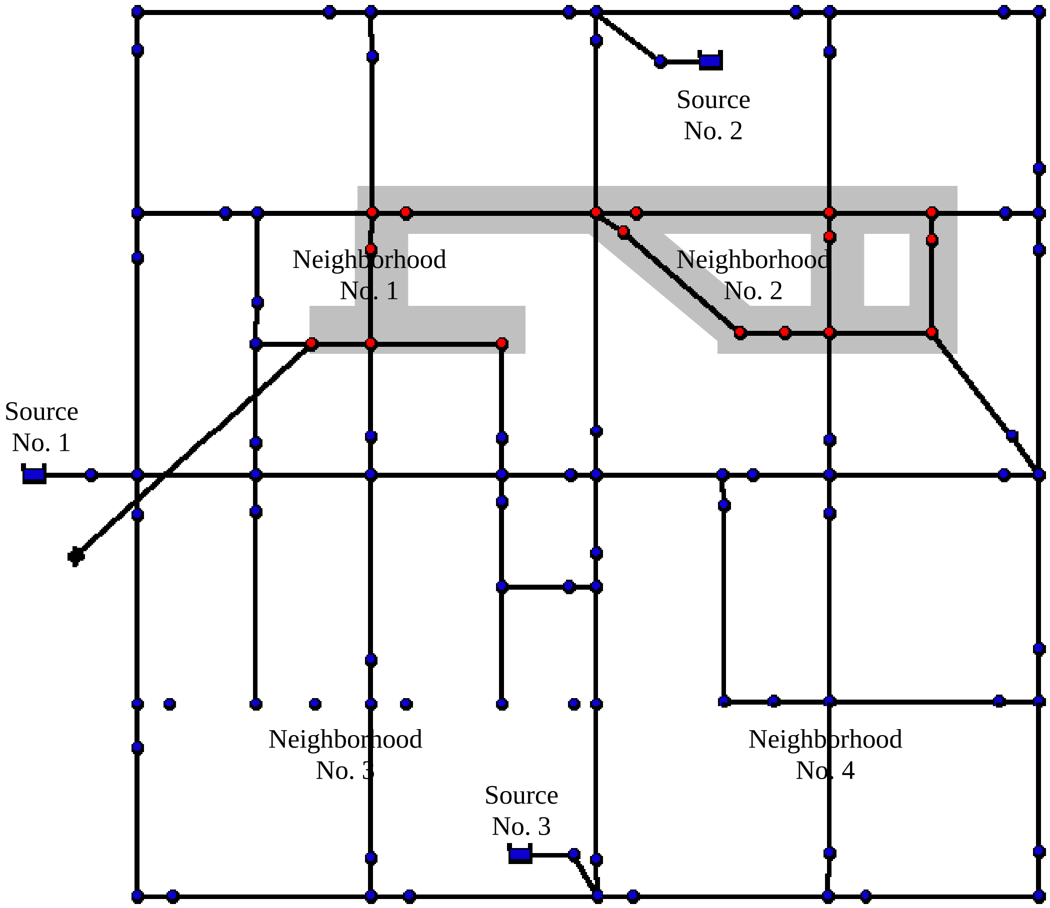

Figure 3-11: Contaminant at Neighborhood No. 1, Source No. 1 open, No. 2 & 3 closed.

Note: Shaded areas denote contaminated pipelines

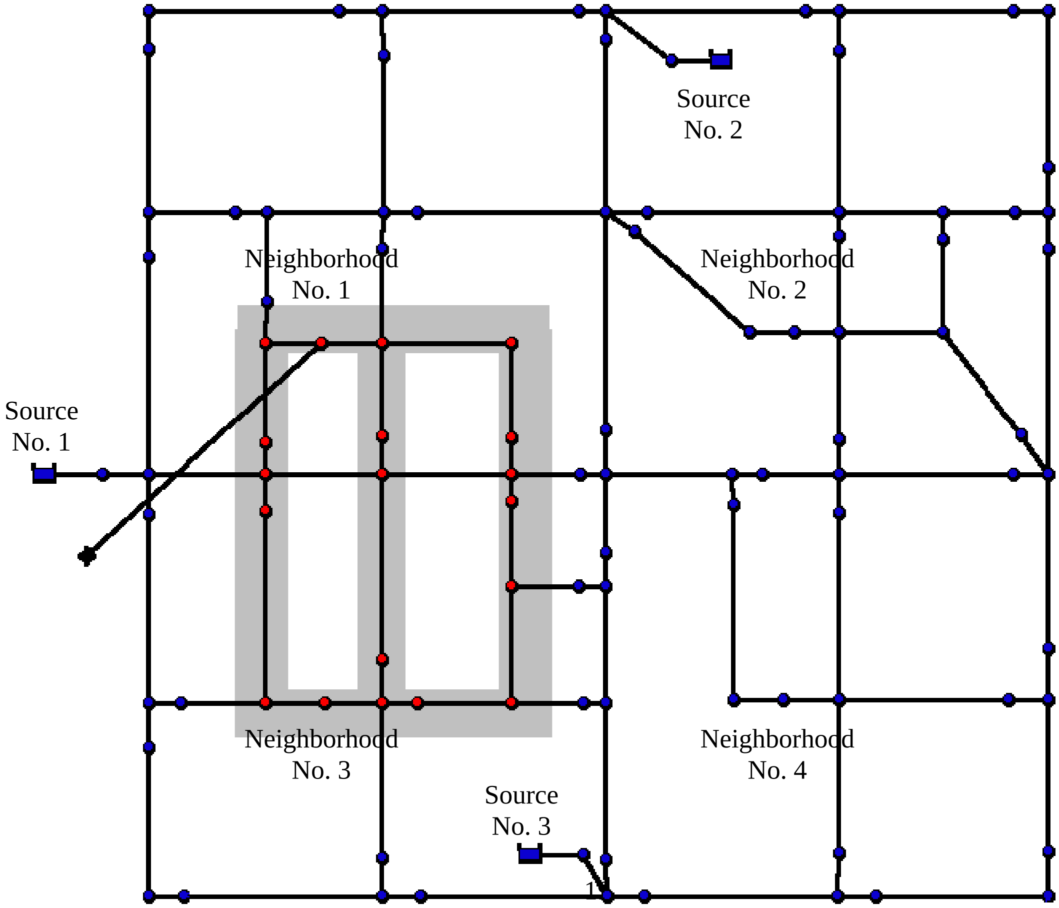

Figure 3-12: Contaminant at Neighborhood No. 1. Source No. 2 open, No. 1 & No. 3 closed

Note: Shaded areas denote contaminated pipelines

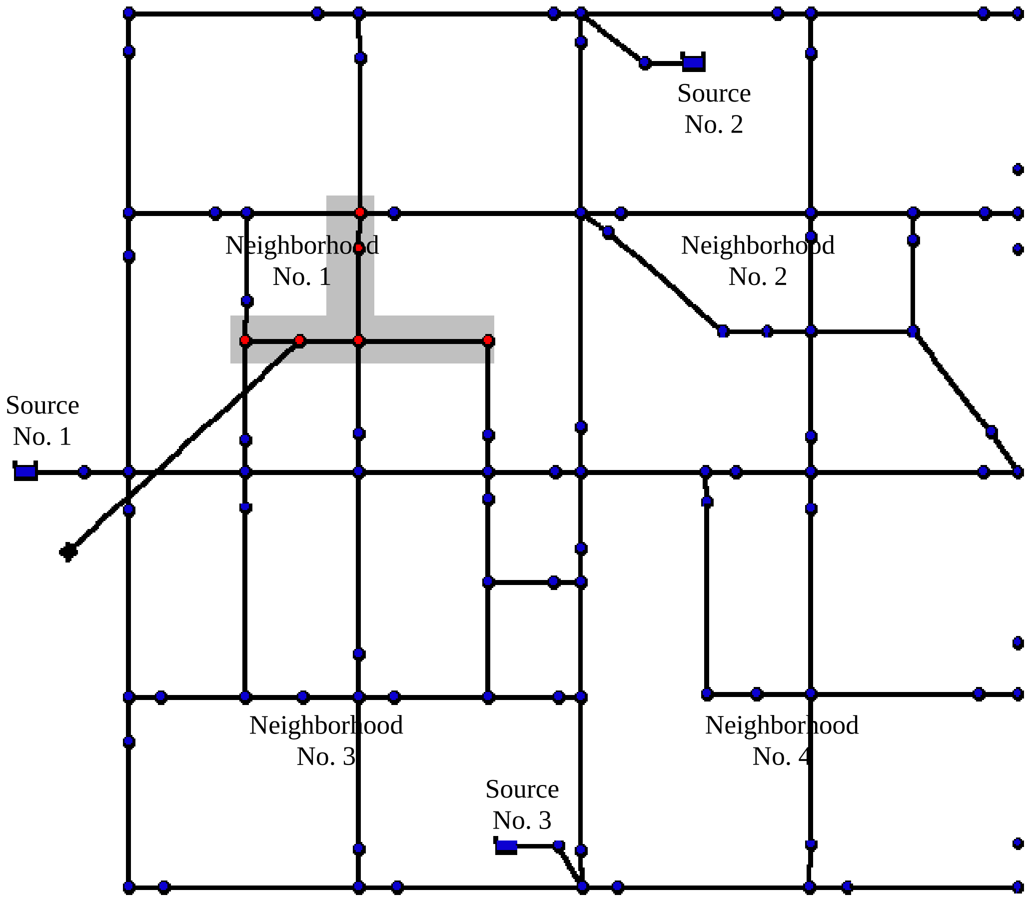

Figure 3-13: Contaminant at Neighborhood No. 1, Source No. 3 open, No. 1 & 2 closed.

Note: Shaded areas denote contaminated pipelines

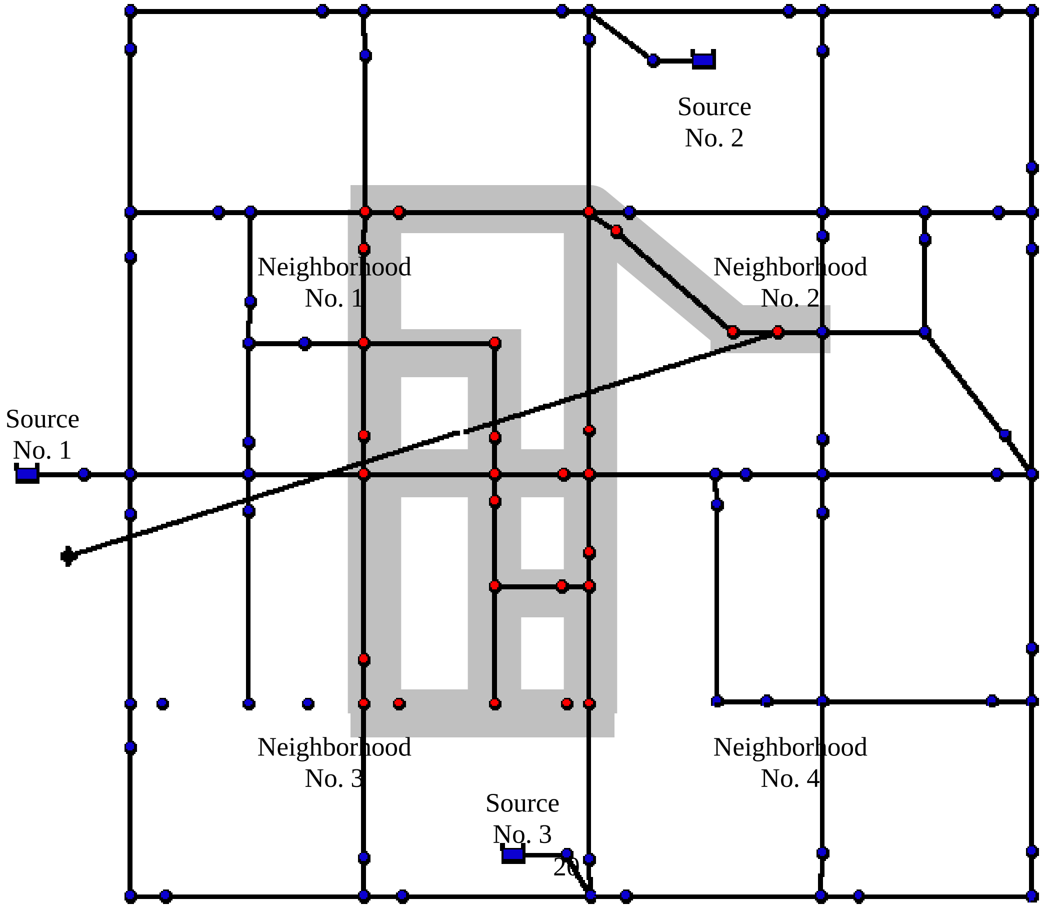

Figure 3-14: Contaminant at Neighborhood No. 2. Source No. 2 open, No. 1 & No. 3 closed

Note: Shaded areas denote contaminated pipelines

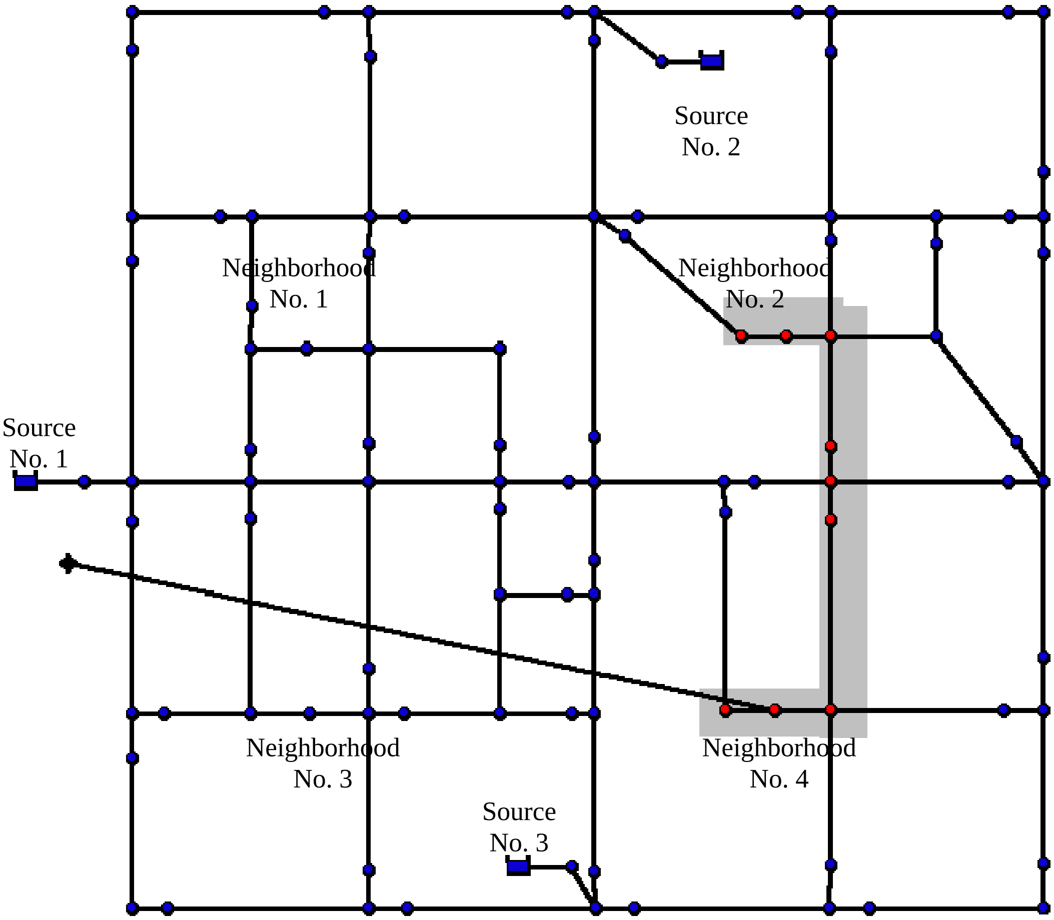

Figure 3-15: Contaminant at Neighborhood No. 3, Source No. 3 open, No. 1 & 2 closed.

Note: Shaded areas denote contaminated pipelines

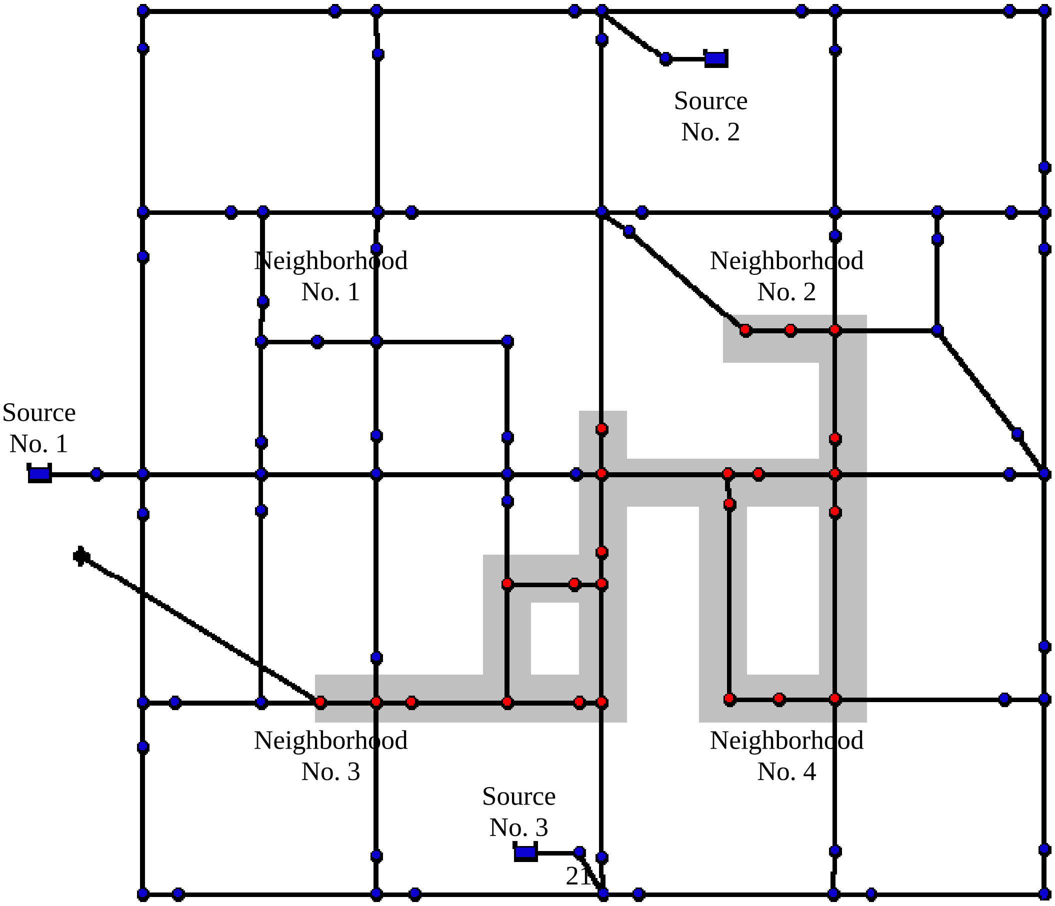

Figure 3-16: Contaminant at Neighborhood No. 4. Source No. 2 open, No. 1 & No. 3 closed

Note: Shaded areas denote contaminated pipelines

Based on these results there are a couple of conclusions that can be drawn. The extent of contamination is independent of pumping rate and time. System demand and the location of the contaminant with respect to the source feed appear to dictate how far and how fast a contaminant will propagate through the system. As illustrated in the figures, the closer a contaminant was introduced to a source of water, the more damage it caused. Because of this, when a source is contaminated (storage tank, pumping facility or transmission main) the entire area should be assumed to have been contaminated.

In addition to the contamination analysis, a test was run to determine whether there is a relationship between the initial concentration of the contaminant and the volume of water contaminated in the distribution system. In this analysis four alternatives were tested (i.e., alter initial concentration at (i) neighborhood location No. 1 with only source 1 open, (ii) neighborhood location No. 4 with only source 1 open, (iii) source 1 with all other sources closed, and (iv) source 1 with all other sources open). To perform the analysis the initial concentration was changed using the following values: 500,000; 100,000; 10,000; 1,000; 100; 10; 1.0; and 0.1 mg/L. The volume of contaminated water was computed. A pipe is judged to be contaminated if the junctions on both ends of the pipe have contaminant concentration greater than a desired threshold. The U.S. EPA drinking water standards for the contaminant in question were used as thresholds.

The results of this analysis are reported in Table 3 and are shown in Figures 4. Table 3 shows the volume of water contaminated for different concentrations of contaminants.

Table 3 – Initial concentration vs. volume of water contaminated

Concentration (mg/L)	NEIGHBORHOOD NO. 1 Volume (ft^3)	NEIGHBORHOOD NO. 4 Volume (ft^3)	†SOURCE NO. 1 Volume (ft^3)	‡ SOURCE NO. 1 Volume (ft^3)
500000	6,522.9	4,781.1	76,812.6	24,158.5
100000	6,522.9	4,781.1	76,812.6	24,158.5
10000	6,522.9	4,781.1	75,139.7	24,158.5
1000	6,522.9	3,897.8	75,139.7	24,158.5
100	6,522.9	3,014.4	72,489.7	24,158.5
10	6,847.5	3,014.4	0.0	24,158.5
1	1,231.1	3,014.4	0.0	24,158.5
0.1	1,214.4	1,221.1	0.0	0.0

† This scenario is when only source No. 1 is open and the other two sources were closed
‡ This scenario is when all three sources are open

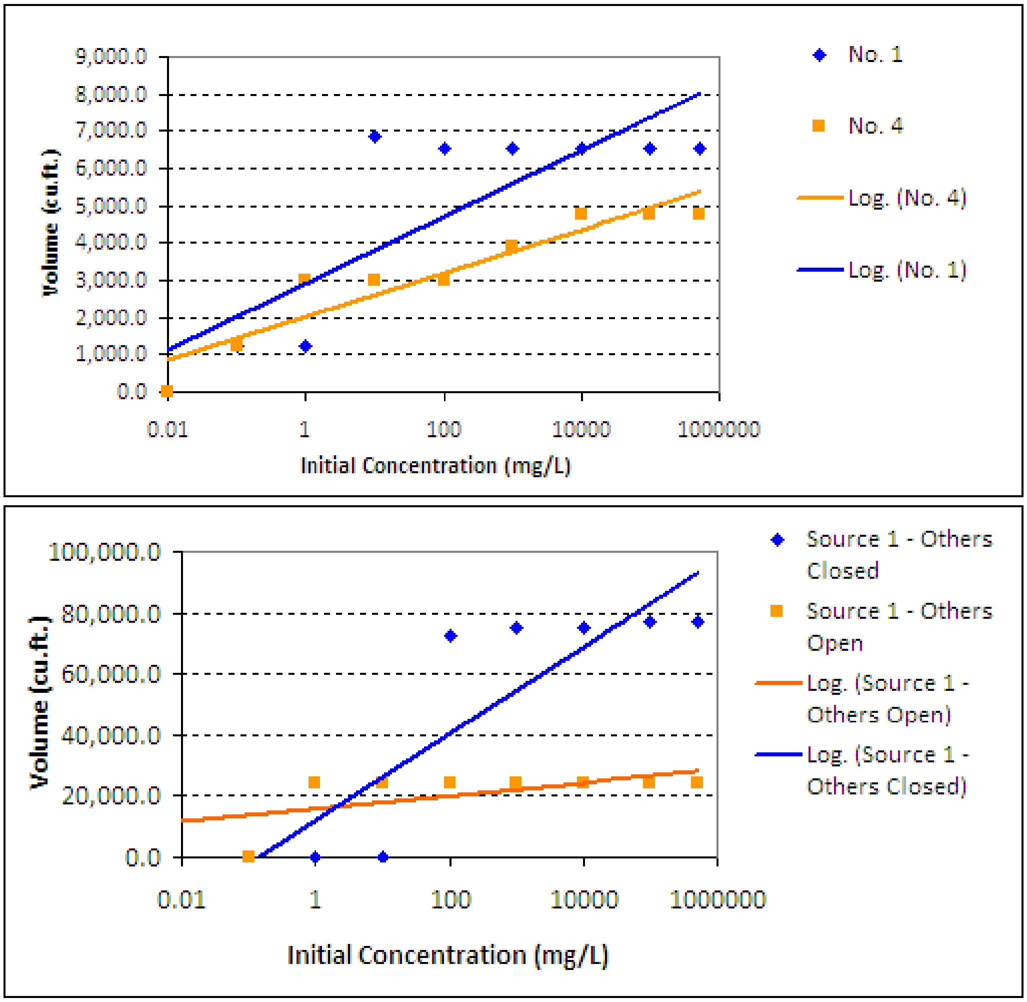

Figure 4 Initial concentration vs. volume of water contaminated

The graphs in Figure 4 indicate that rather than having a linear relationship between the contaminant's initial concentration and the volume of water contaminated, there is a threshold concentration e.g., 100 mg/L for source contamination. When there is sufficient contaminant introduced into the pipeline at the source, then it will contaminate the entire network served by that source. In other words a contaminant need not be introduced at its maximum soluble concentration in order to be harmful.

3.2 Clean-up Results. Table 4 summarizes the results of the decontamination scenarios by showing the amount of time as well as the volume of water contaminated.

Table 4: Clean-up time and volume of water required for flushing and decontamination

Procedure	Alternatives	Description	Clean Up Time	Volume (Mgal)	No. to Truck loads required (2000 gallons capacity)
Flush	1	All Taps Open	62 hrs	8.56	4,280
Flush	2	Fire Hydrants Open	6.5 hrs	2.46	1,230
Flush	3	Both Taps and Hydrants Open	6 hrs	2.35	1,175
Decontaminate	4	3 Fire Hydrants Open	7 hrs	1.89	945

Flush 1: Clean-up with all "taps" open (use Peak Hour Scenario) for longer period until completely clean.

Flush 2: Clean up scenario with "hydrants" open with "taps" closed.

Flush 3: Clean up scenario with "hydrants" and "taps" both open.

Decontaminate 4: Introduce NaOH to system and then place a demand on one or more "Hydrants" or somewhere else in the system. These hydrants are used to remove the contaminated water.

20,000 mg/L (Initial concentration of NaOH being introduced to the system)
0.000004 mg/L (minimum residual NaOH in system to ensure treatment)

Results show that the least amount of time required (6 hours) and minimum volume of water (2.35 Mgal) for clean-up of contamination would be under flushing alternative 3 (i.e., when both taps and fire hydrants are operated). Decontamination takes 7 hours but generates less contaminated water (1.89 Mgal). In addition, the results show that opening taps is less effective (more time consuming) than opening fire hydrants to flush the system.

The volume of water in Table 4 represents the amount of contaminated water that must be handled at the treatment facility, or discharged into the storm water channels. For certain contaminants, flushing the system through the taps in homes or fire hydrants and disposing contaminated water into sewer or storm water drain may not be a safe option. Under that scenario, the contaminated water may need to be transported via trucks to a treatment facility or safe discharge location. A typical water truck used in construction practice can hold approximately 2,000 gallons. Some larger trucks can hold as much as 4,000 gallons, but may not be as readily available. Considering both cases, between 613 and 1,230 trucks will be required for alternative No. 2 (i.e. when fire hydrants are operated). For alternative 4 (i.e. decontamination), between 473 and 945 trucks would be required to haul the contaminated water to the treatment facility. The time reported in Table 4 does not include time to mobilize a convoy, or the swing and loading (fill) time between trucks. A local emergency disaster response and preparedness plan may need to consider the time required for truck mobilization.

4. Conclusions

The following conclusions can be drawn from the study.

- EPANET proved to be a successful tool to study the spread to contaminant in the water distribution system. The model was also successful in evaluating flushing and decontamination scenarios. One limitation of EPANET is that it can only handle one contaminant at a time.

- Contamination of the water source is more critical than contamination of a neighborhood location.

- Water systems with multiple storage tanks (sources) have more flexibility in limiting the spread of the contaminant and in handling the clean-up/decontamination.

- It is possible to contaminate a small water distribution system using a contaminant in amounts that are commercially available and transportable.

- It is possible to contaminate a small water distribution system in a few hours even with low pumping rates of a contaminant.

- Fire hydrants are more effective in flushing the contaminant from a water system than opening taps in homes.

- Once a water sources is contaminated, it is likely that the entire system will need to be flushed, generating large amounts for water to be treated or disposed off.

- The decontamination procedure to be used depends on the type of contaminant but flushing with water, changing pH levels, and adding neutralizing solutions or disinfectants are potential options for clean-up.

5. Recommendations and Security Implications

- Although general conclusions can be drawn, every water system is unique and should be modeled individually. Water utilities that already have a water system model should modify that model to include contaminant transport. Towns that do not have a water distribution model can use existing drawings of the system layout and water demands to create a model. They can use a similar approach used in this study to understand how water moves in their system and which sources and neighborhood locations are critical. They can evaluate potential actions to be taken in case a contamination incident occurs.

- Water utilities should pay special attention to protecting the water sources (reservoirs, storage tanks), especially the tanks that are located upstream and feed the largest portion of the system.

- Even though contaminating a neighborhood location is less critical, water utilities should pay attention to protecting neighborhood locations that feed hospitals or schools.

- Although the amount of contaminant required to contaminate a larger water system may be difficult to obtain and deploy, small water utilities should not underestimate the potential to contaminate a system because, for most highly toxic chemicals, only a small amount of contaminant is required. If a contaminant is introduced to a neighborhood location using a truck mounted pump the system could be contaminated in a short duration.

- Water utilities should avoid feeding the entire system from one storage tank. Instead multiple smaller tanks should be considered.

- Because of higher flow rates and location, fire hydrants should be used to flush contaminated systems rather than opening taps in homes.

- Water utilities should estimate the volume of water that will be contaminated. With this estimate they should evaluate if their sewer system and storm water system will be able to handle the contaminated volume flushed through fire hydrants. If not, provisions should be made to build temporary storage (e.g. ponds).

- If water is contaminated with a compound that would affect the operation of a waste water treatment plant (e.g. compounds that are toxic to bacteria), then contaminated water would have to be transported by trucks to storage ponds where it could be treated. Even for a small system the number of tuck loads required is very large.

- The U.S. Environmental Protection Agency (EPA) has compiled a list of potential contaminants for water systems. Water utilities should select inorganic, organic and biological contaminants from that list with low contaminant thresholds and run models to prepare for worst case contamination scenarios.

- Water utilities should determine the amount of disinfectant required to clean up the system. This amount is what they would need to procure in a timely manner in case of an incident.

- Water utilities should explore the possibility of decontaminating the system by pH (measure of the acidity or alkalinity of a solution) changes; there are several inorganic contaminants that are less toxic at different pH levels.

- Water utilities should identify the locations (e.g. storage tank or fire hydrant) in the water system where disinfectants or decontaminating compounds should be added to provide for effective clean-up.

6. References

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