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Spread of Emerging Contaminants in Water Distribution Systems

Danielle Pilarski
Michigan Technological University, dcscott@mtu.edu

SPREAD OF EMERGING CONTAMINANTS IN WATER DISTRIBUTION SYSTEMS

By

Danielle Pilarski

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Department of Civil and Environmental Engineering

Thesis Advisor:	*Brian Barkdoll*
Committee Member:	*Melanie Kueber Watkins*
Committee Member:	*Gordon Patterson*
Department Chair:	*Audra Morse*

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Abstract

Emerging contaminants are a growing concern to humans and the environment. Studies have shown these contaminants are present in the environment through continuous release into surface waters from wastewater treatment effluent, manufacturing processes, and agricultural use. The effects of these contaminants have been observed in ecological studies, but they have not yet been well studied for long term exposure in humans. These emerging contaminants have also not been well studied to determine the rates at which they decay or how they move through distribution systems. This study aims to determine the importance of decay rate on concentration throughout a distribution system, as well as determine how the layout of a system effects concentration. Systems were modeled using EPANET 2 to determine the time to peak contamination for a clean system becoming contaminated, as well as a contaminated system being cleaned of contamination. It was found that only emerging contaminants with second order decay at the highest rate observed did not build up to high concentrations in the systems. The position of storage tanks in the distribution system effected the rate at which contaminants cleared the system, and systems with a branched layout could be cleared of contamination faster than systems containing loops. Further study is needed to determine the decay rates of these emerging contaminants, how to remove them during wastewater treatment processes, as well as their long-term effects on humans so that these contaminants can be effectively monitored and remediated.

1 Introduction

Emerging contaminants consist of natural and manufactured chemicals, such as pharmaceuticals, personal care products, hormones, illicit drugs, pesticides, and microorganisms which have only recently come to light as potential contaminants of concern (CoC) to human and environmental health. Many of these contaminants are known in controlled doses to be therapeutic, carcinogenic, or cause endocrine disruption, but are not yet well studied to determine the potential effects of long-term low-level exposure on humans (Sauvé and Desrosiers, 2014). The Safe Drinking Water Act of 1974 began to establish maximum contaminant levels (MCL's) for emerging contaminants and this list continues to expand today, but many CoC's have yet to be studied sufficiently to create MCL's (APEC, 2016).

While the effects of many emerging contaminants have not been well studied in humans, effects are being seen in the ecology of surface waters. A study by Arnnok et al. (2017) found surface water concentrations and bioaccumulation of pharmaceuticals in the brains, livers, and other tissues of fish near wastewater treatment plants on the Niagara River. The primary CoC's found in the river were SSRI antidepressants including sertraline at concentrations up to 218 nanograms per liter (ng/L), bupropion at up to 217 ng/L, 387 ng/L of venlafaxine, citalopram at 188 ng/L, and the antihistamine diphenhydramine at up to 252 ng/L. The fish were observed for behavioral changes resulting from exposure to the found CoC's and showed a reduction in growth rates, feeding rates, hunting capability, and survival instincts. The fish were also found to no longer release the stress hormone cortisol in response to threats after exposure to SSRI's. A study by Khan et al. (2017) looked at environmental concentrations of 15 pharmaceuticals found on the U.S. Food and Drug Administration's (FDA) flush list to determine if they accumulated in the environment in quantities which could pose a risk to human health. Using both measured and predicted concentrations this study determined that the environmental concentrations were likely a negligible risk to humans, but it is not possible to be certain without further study of the effects of long-term exposure to low concentrations of these contaminants.

Emerging contaminants are continuously released into surface waters not just through manufacturing processes and crop treatment runoff, but also through treated wastewater (APEC, 2016; Arnok et al., 2017; Gibs et al., 2007; Haddad et al., 2015; Sauvé and Desrosiers, 2014). Traditional wastewater treatment processes do not remove many emerging contaminants and more than half of the CoC's tested in a study by J. Gibs et al. (2007) did not degrade from chlorination during a typical timespan drinking water would reside in a water distribution system. Effluent from wastewater treatment plants into Lake Michigan have been tested for 32 pharmaceuticals with concentrations of 0.3-9,200 ng/L found (Arnok et al. 2017). Treatment options for removing contaminants such as pharmaceuticals and personal care products vary depending on the chemical. Activated sludge treatment systems and lagoons have been implemented in some areas, and show promise in removal of many emerging contaminants (Lishman et al., 2006). A study by Lishman et al. (2006) looked at the effectiveness of lagoons, activated sludge, and activated sludge plus filtration as treatment options for emerging contaminants. They found that

acidic pharmaceuticals such as ibuprofen and naproxen had high removal rates of around 93% in activated sludge, while other pharmaceuticals had removal rates between 23-66%. Musk fragrances and triclosan were found to have up to 98% removal rates using lagoon treatments, but lower removal rates in activates sludge treatment systems. Another treatment option for the removal of pharmaceutical contaminants is photocatalysis. A study by Kanakaraju et al. (2014) studied the effectiveness of using titanium dioxide as a photocatalysis agent. They found that this method was highly effective at removal of a wide variety of pharmaceuticals but required further study due to inconsistencies in removal rates found between studies.

Water enters a drinking water distribution system when surface water is taken in by a water treatment plant, processed through filtration systems, disinfected by chlorination, and pumped into the distribution system's reservoir, or from groundwater which can either be chlorinated at the well site and pumped into the distributions systems reservoir or run through a treatment station prior to entering the reservoir (APEC, 2016). From the reservoir the water is pumped through the distribution pipes and into storage tanks, homes, and businesses. Monitoring done by the state of Arizona's Department of Environmental Quality (AZ DEQ) has tested and found 109 emerging contaminants detectible in their surface water including the Colorado River, groundwater, reclaimed wastewaters, and even in their drinking water. Emerging contaminant categories found in Arizona drinking water included pharmaceuticals, personal care products, industrial chemicals, flame retardants, herbicides and pesticides, surfactants, and micro-organisms. They did not find illicit drugs, steroids, or cyanotoxins in the drinking water, however they did detect these in some surface water and groundwater. This study does not report the concentrations detected in drinking water, but they do report values for some emerging contaminants in the Colorado River at a range of 0.2-447 ng/L (APEC, 2016).

The movement of the water through water distribution systems can be modeled using programs such as EPANET 2.0 which can be used to perform long-term simulations of hydraulics and water quality in water distribution systems. It is used commonly used design, upgrade, and optimize distribution systems, and to model water age and quality. The hydraulic modeling of EPANET 2 can account for a wide range of size for systems, pipe lengths and diameters, tank sizes, as well as variable pumps, demands, opening and closing of valves, pressure regulators and more. The water quality modeling of EPANET 2 includes water age, growth and decay of chemicals, water mixing, the movement of chemicals and water, and more. It is a useful tool that can be used to model a wide variety of scenarios within a water distribution system (Rossman, 2000).

Studies are lacking on the behavior of emerging contaminants in distribution systems, but studies have been done on other chemicals, especially dealing with chlorination. One such study by Boano et al. (2016), used EPANET 2.0 to model the age of water in a distribution system to calculate the formation of chlorate in distribution systems from chlorination during water treatment processes. It was found that chlorate formed at much lower levels than the limits proposed by the World Health Organization (WHO), but that a lack of data on pipe characteristics could be affecting the accuracy of the study. Another study by Clark

et al. (1993) modeled the concentrations of chlorine residuals and found that water quality was significantly affected by variations in system operations and storage time in tanks.

This study aims to determine how these emerging contaminants move through various water distribution systems to determine how quickly these CoC may build up at various points through a system if the source were to become contaminated at a known concentration, how quickly they can be cleared from a system if the source could be cleaned up, and how the concentrations may vary and fluctuate with normal operation of a system. It was hypothesized that higher order of decay and higher decay coefficients would result in less buildup in the system. The time to contaminate is expected to correspond to relative distance from the source reservoir. Time to contaminate and time to clear are both predicted to be proportional to the total volume of the system. Looped systems are predicted to clear more quickly than branched due to the increased pathways to circulate clean water into the system, and systems with tanks would take longer to clear than without tanks due to the additional storage time of contaminated water within the tanks. Fluctuations in contaminant concentration are expected to be seen due to changes in system operations and with changes in tank storage as seen in Clark et al. (1993), however it is predicted that the location in the tank within the system will affect the amount of fluctuation observed. It was also hypothesized that the time for a system to become contaminated or clear of contaminant would be sensitive to the value of the decay coefficients across the same order of decay. The results of this study may help further studies determine what levels of exposure a person may experience based on the type and size of water distribution system and the decay rates of the individual emerging contaminant being investigated.

2 Methods

Thirteen pre-existing systems of various sizes and layouts were modeled using EPANET 2 with system patterns and defaults left as-is for each system. Quality options were set to 'chemical', in units of micrograms per liter (µg/L). The chemical was added at the source as an initial and constant continuous input. Reaction options were set to a range of bulk reaction orders and coefficients calculated based off experimental data by J. Gibs et al. (2007) to determine to remaining fraction of known initial concentrations of several emerging contaminants in glass jars of chlorinated tap water over a 10 day study. For each chemical a bulk decay coefficient (K_b) was calculated as zero order decay by plotting concentration vs. time for the 10 days and the equation $slope = -K_b$, as first order decay by plotting the natural log of concentration vs time and the equation $slope = -K_b C$, where C = concentration, and as second order by plotting the inverse of concentration vs time and the equation $slope = K_b$. A zero order reaction is independent of the concentration of the contaminant, first order is directly proportional to the concentration, and second order is directly proportional to the square of the concentration of the contaminant (Flowers et al., 2018). EPANET calculates the decay rate from K_b according to the equation $r = K_b C^n$, where C = the concentration of the contaminant, and n = the reaction order (Rossman, 2000). The high and low value of K_b, shown in **Table 2.1**, were used for each order of decay with the low decay coefficients representing a slow rate of decay, and high decay coefficient representing a more rapid rate of decay. The corresponding half-life ($t_{1/2}$) for each K_b was calculated for comparison of the relative magnitude using the equations $t_{1/2} = \frac{C_0}{2K_b}$ for zero order, $t_{1/2} = \frac{\ln 2}{K_b}$ for first order, and $t_{1/2} = \frac{1}{K_b C_0}$ for second order. Due to the lack of published data regarding the decay of emerging contaminants, the chemicals were assumed to have no wall reactions for this study.

Table 2.1 Calculated values of K_b and their corresponding half-life

		Low	High
Zero Order	K_b (µg/L/day)	-0.00055	-0.38505
	$t_{1/2}$ (days)	90,909	130
First Order	K_b (1/day)	-0.00027	-0.07279
	$t_{1/2}$ (days)	2,567	9.5
Second Order	K_b (1/(day*µg/L))	-0.00008	-0.04350
	$t_{1/2}$ (days)	125	0.23

The surface water sources of the systems were set to a concentration of 100 µg/L. While this value is higher than concentrations which have been observed in studies such as by Arnok et al. (2017) which reports pharmaceuticals being found in the range of 0.3-9,200 nanograms per liter (ng/L) in the waters of Lake Michigan, EPANET is only capable of calculating out to hundredths of a µg/L (Rossman, 2000), so a higher concentration was selected and percent of initial concentration was used to compare between systems. Each system was run until the pattern of contamination levels in the selected nodes reached 100% of the source contamination level, or a peak concentration was reached and values began to repeat. Three junctions were selected to observe from each system, one taking the longest to become contaminated, one being geographically distant from the sources, and one being centrally located in the system.

Each system was then set to 100 µg/L in each junction and storage tank, with a concentration of 0 µg/L in the source reservoirs to model clearing of the system if the contaminant were to be removed from the source. The systems were run until the observed junctions reached a concentration of 0 µg/L.

A system was then selected to repeat these processes to monitor across a range of first order K_b values from -0.00001/day to -0.5/day to determine if the time to become contaminated and time to clear contaminant was sensitive to the value of K_b. This range was selected because it was a slightly wider range than the highest and lowest values of K_b calculated across all orders of decay. These decay coefficients represent a half-life range from 69,315 days for K_b = -0.00001 to 1.4 days for K_b = -0.5. Results were then grouped into systems with the following characteristics to attempt to find trends: branched, looped, tanks near the source, tanks far from the source, and no tanks.

3 Results

System 1 was observed at Junctions 54, 90, and 121 as shown in **Figure 3.1.a**. Junction 54 was chosen to observe as the longest time to reach peak contamination, Junction 90 was chosen for its location near the center of the system, and Junction 121 was chosen as a junction geographically distant from the reservoir. At Junction 54 the maximum time to peak concentration, shown in **Figure 3.1.b**, was 651 hours to reach a peak concentration of 99.09% with a zero order K_b of -0.038505 µg/L/day. The minimum time to peak concentration was 340 hours to reach a peak concentration of 100% with a zero order K_b of -0.00055 µg/L/day. In **Figure 3.1.c**, Junction 90 had a maximum time to peak concentration of 631 hours to reach a peak concentration of 98.80% with a second order K_b of -0.00008 day*µg/L, and a minimum time to peak concentration of 8 hours to reach a peak concentration of 50.93% with a second order K_b of -0.04350 day*µg/L. Junction 121, seen in **Figure 3.1.d**, had a maximum time to peak concentration of 613 hours to reach 94.52% of the source concentration with a first order K_b of -0.07279/day, and a minimum time to peak contamination of 114 hours to reach 34.75% with a second order K_b of -0.04350 day*µg/L. **Figure 3.1.e** shows the maximum time to flush all contamination from Junction 54 was 279 hours to reach 0% of the initial concentration for all values of K_b used except for the zero order K_b of -0.38505 µg/L/day which took only 162 hours to reach 0%. For Junction 90, the maximum time to flush all contamination, shown in **Figure 3.1.f**, was 247 hours for all values of K_b used except for the zero order K_b of -0.38505 µg/L/day which took 151 hours. Junction 121, in **Figure 3.1.g**, had a maximum time to flush all contamination of 233 hours for a first order K_b of -0.00027/day and second order K_b of -0.00008 day*µg/L. The minimum time to flush all contamination from Junction 121 was 128 hours for a zero order K_b of -0.38505 µg/L/day. A repeating pattern was seen in the concentration values that corresponded to the tank emptying and filling times, but, in addition, a smaller 24-hour fluctuation was seen corresponding to diurnal user demands.

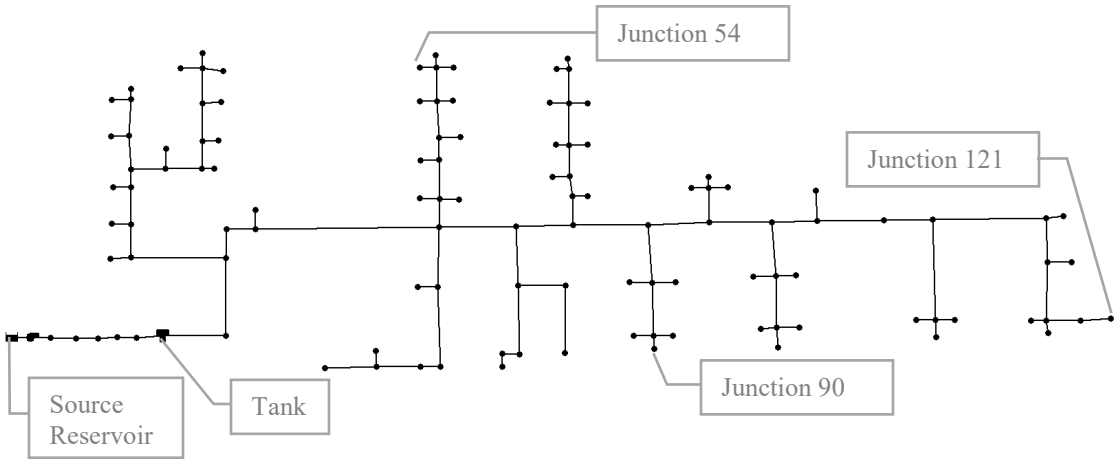

Figure 3.1.a System 1 monitoring junctions.

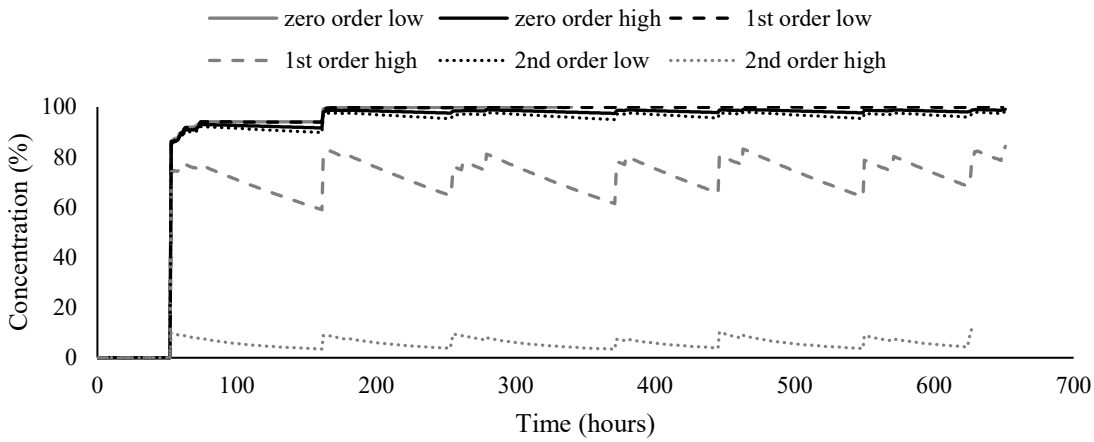

Figure 3.1.b System 1, Junction 54 contaminant spreading history.

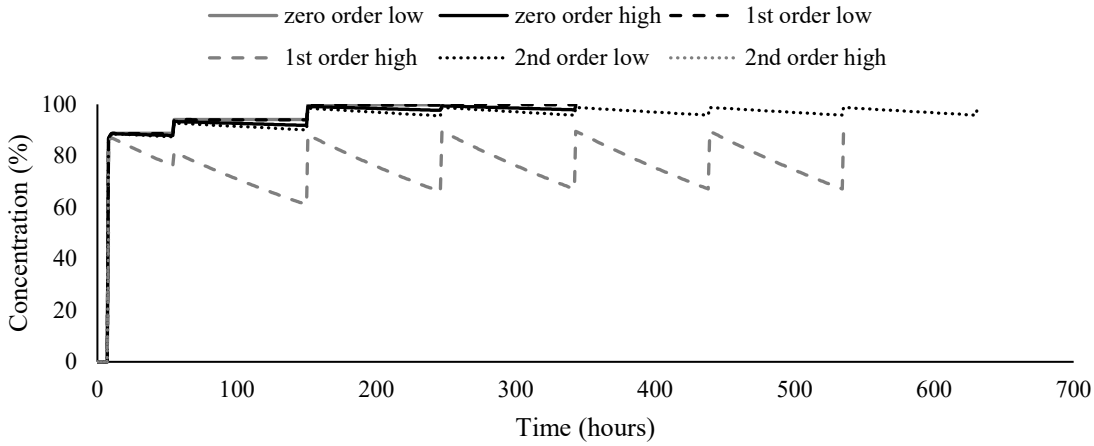

Figure 3.1.c System 1, Junction 90 contaminant spreading history.

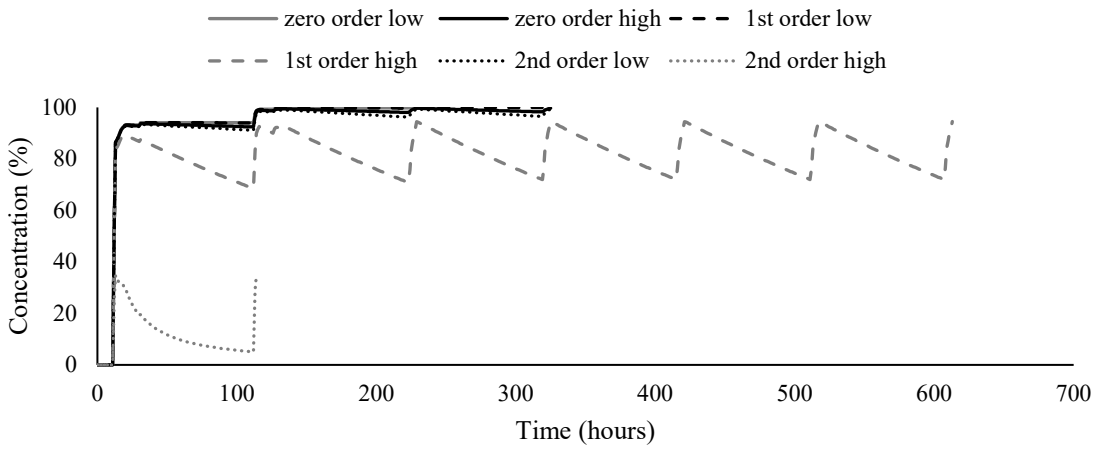

Figure 3.1.d System 1, Junction 121 contaminant spreading history.

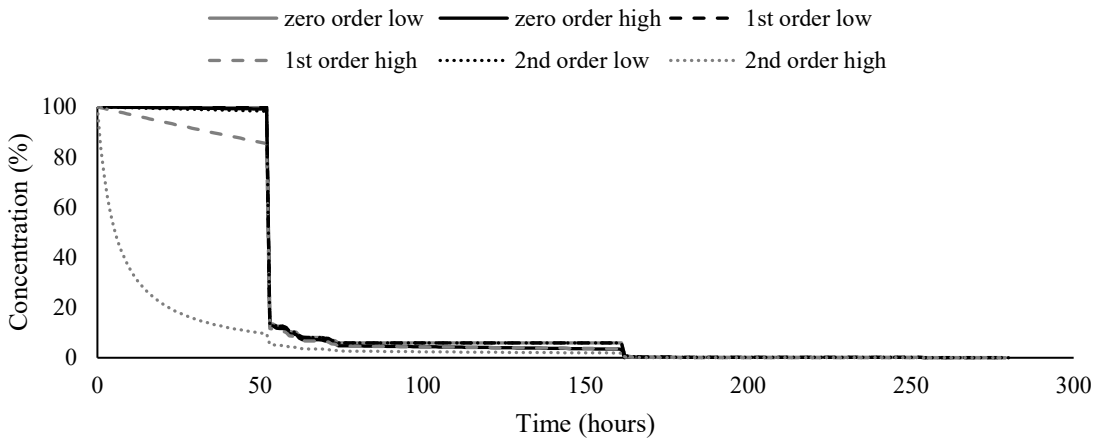

Figure 3.1.e System 1, Junction 54 contaminant clearing history.

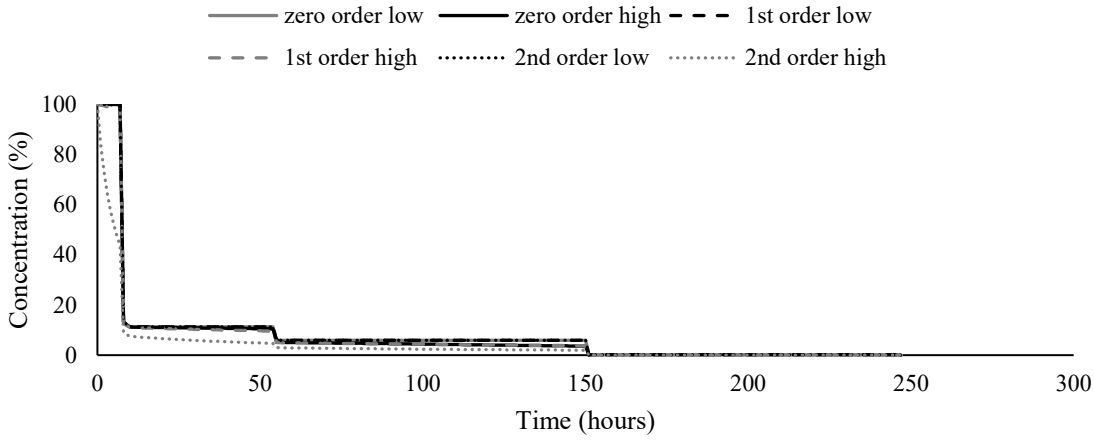

Figure 3.1.f System 1. Junction 90 contaminant clearing history.

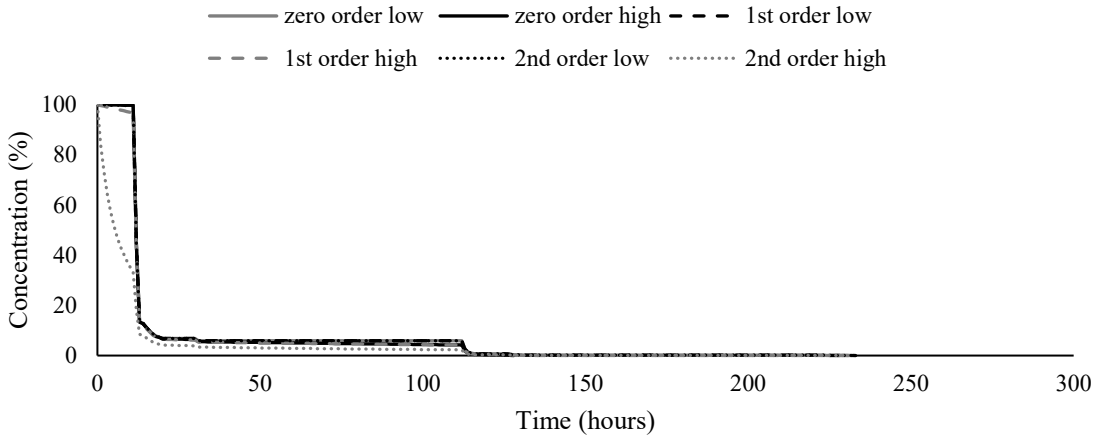

Figure 3.1.g System 1, Junction 121 contaminant clearing history.

System 2 was observed at Junctions 7, 14, and 17 as shown in **Figure 3.2.a**. Junction 7 was chosen to observe as a centrally located point in the system, Junction 14 was chosen as the longest time to reach peak contamination, and Junction 17 was chosen as a geographically distant point from the reservoir. Junction 7, shown in **Figure 3.2.b**, had a maximum time to peak concentration of 248 hours to reach a peak concentration of 100% of the source contamination level with a zero order K_b of -0.00055 µg/L/day. The minimum time to peak contamination was 152 hours to reach a peak concentration of 77.58% with a first order K_b of -0.07279/day. For Junction 14, the maximum time to peak contamination was 273 hours to reach a peak concentration of 99.97% with a first order K_b of -0.00027/day, as shown in **Figure 3.2.c**. The minimum time to peak contamination was 113 hours to reach 99.34% with a zero order K_b of -0.38505 µg/L/day. Junction 17, seen in **Figure 3.2.d**, had a maximum time to peak contamination of 209 hours to reach a concentration of 99.94% with a first order K_b of -0.00027/day. The minimum time to peak contamination was 41 hours to reach a concentration of 12.14% with a second order K_b of -0.04350 day*µg/L. For Junction 7, shown in **Figure 3.2.e**, the maximum time to flush all contamination was 248 hours for all values of K_b used except for the zero order K_b of -0.38505 µg/L/day, which took only 152 hours. Junction 14, in **Figure 3.2.f**, had a maximum time to flush all contaminant from the junction of 186 hours for all values of K_b used except for a zero order K_b of -0.38505 µg/L/day, which needed only 104 hours to reach 0% of the initial contaminant concentration. In **Figure 3.2.g**, the maximum time to flush all contaminant from Junction 17 was 205 hours for a zero order K_b of -0.00055 µg/L/day, first order K_b of -0.00027/day, and second order K_b of -0.00008 day*µg/L. The minimum time needed flush the junction of contaminant was 126 hours for a zero order K_b of -0.38505 µg/L/day.

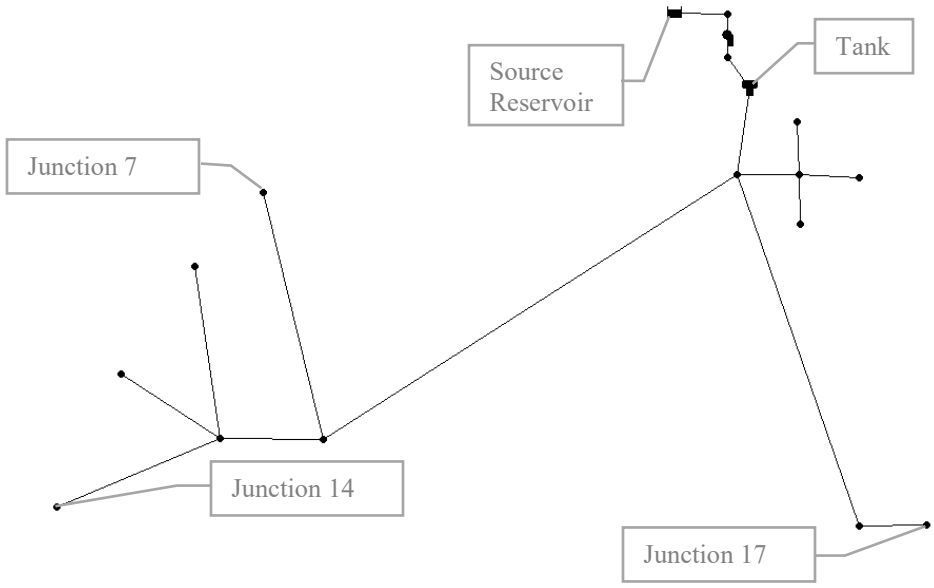

Figure 3.2.a System 2 monitoring junctions.

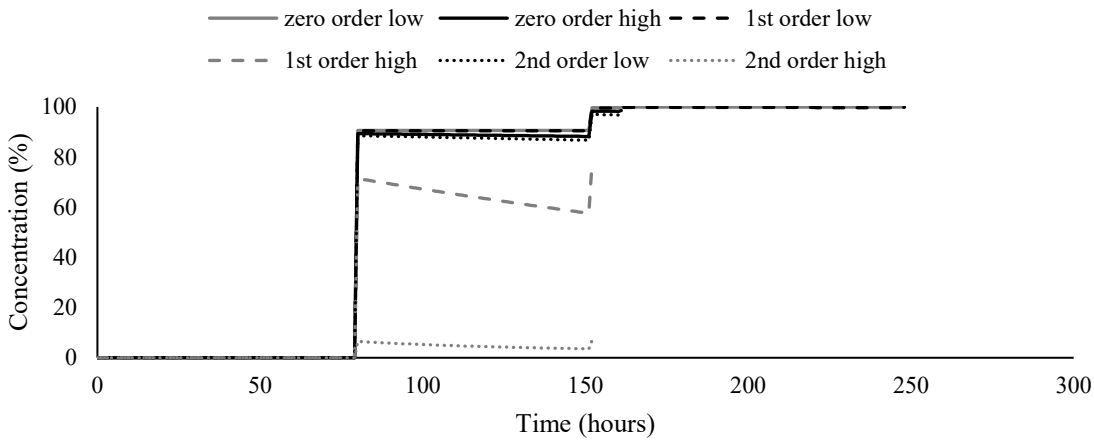

Figure 3.2.b System 2, Junction 7 contaminant spreading history.

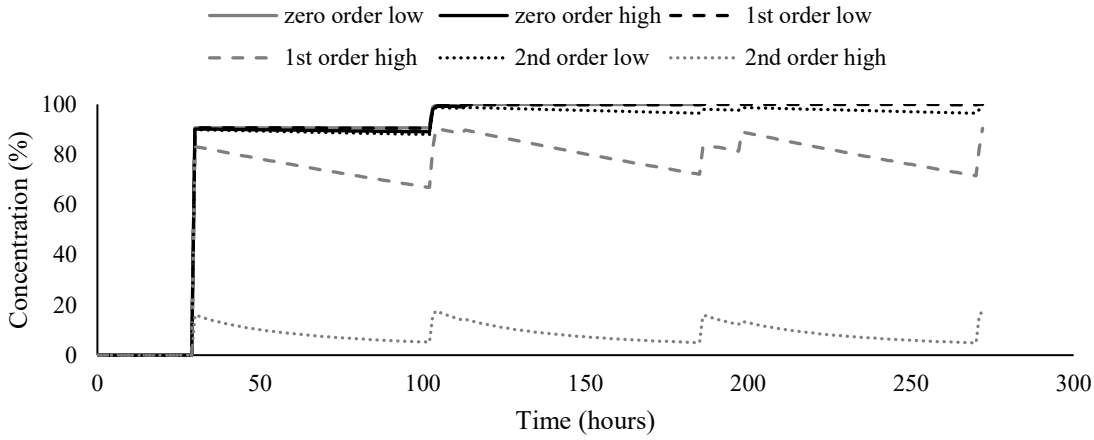

Figure 3.2.c System 2, Junction 14 contaminant spreading history.

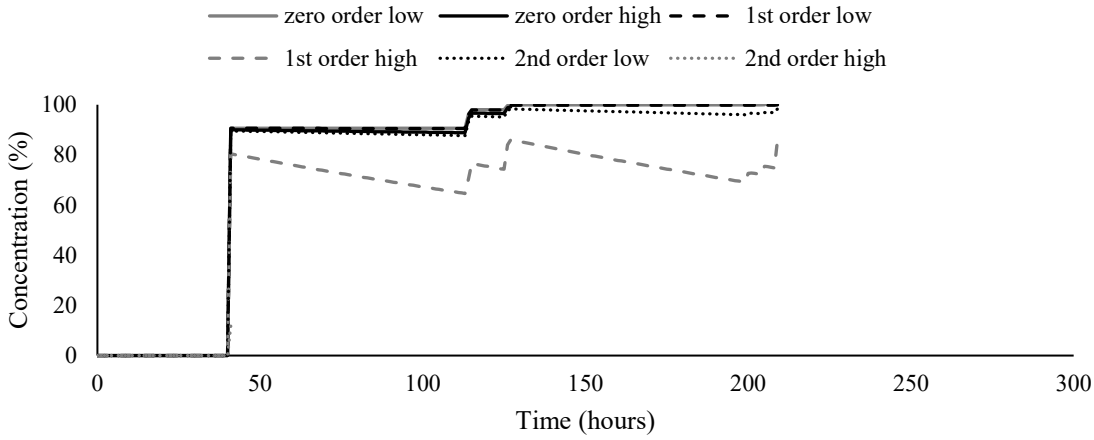

Figure 3.2.d System 2, Junction 17 contaminant spreading history.

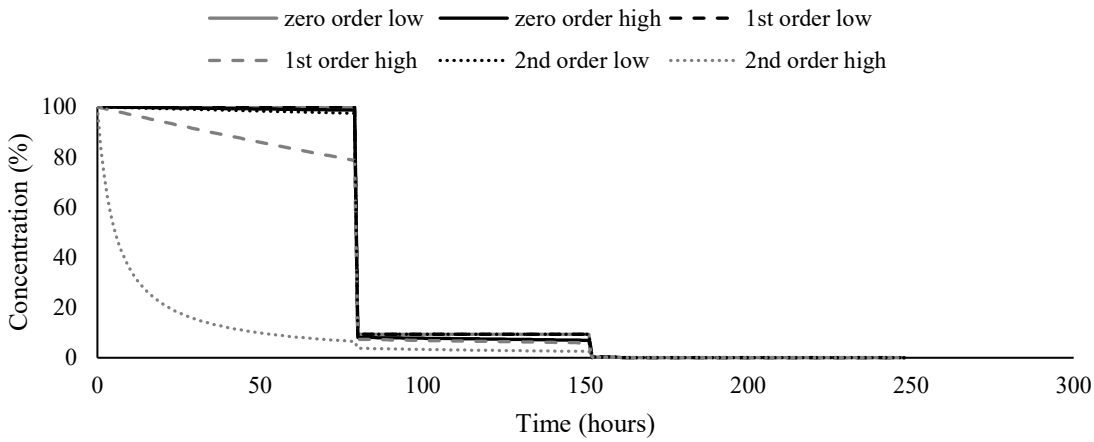

Figure 3.2.e, System 2, Junction 7 contaminant clearing history.

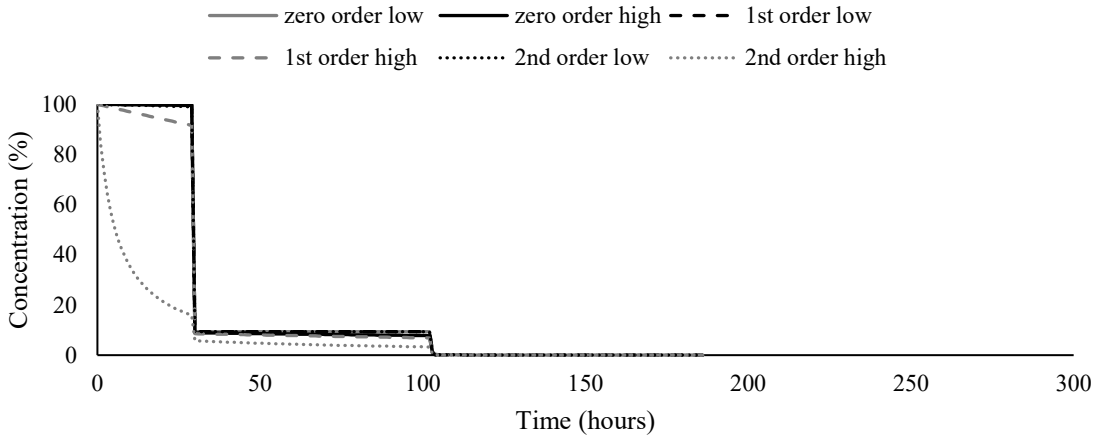

Figure 3.2.f, System 2, Junction 14 contaminant clearing history.

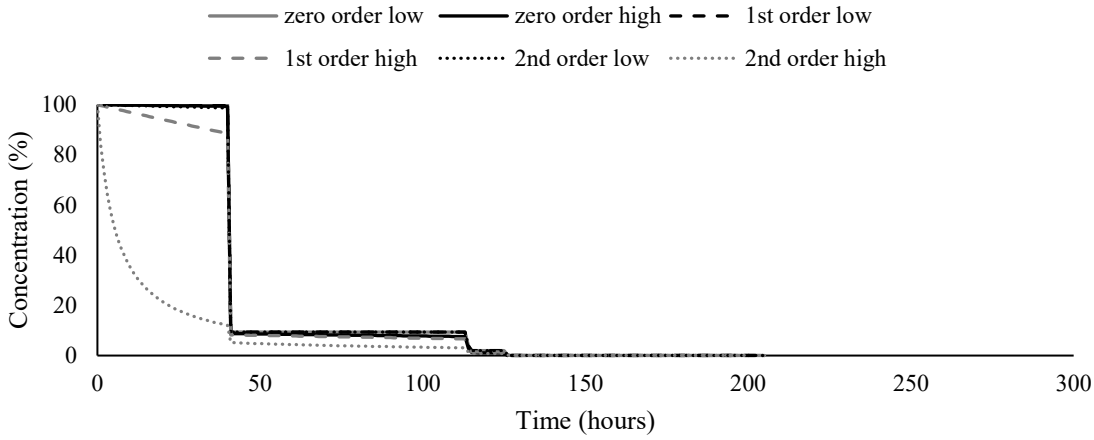

Figure 3.2.g, System 2, Junction 17 contaminant clearing history.

System 3, shown in **Figure 3.3.a**, was observed at Junctions 14, 20, and 25. Junction 14 was observed as a centrally located junction in the system, Junction 20 was the longest to reach peak contamination, and Junction 25 was observed as a geographically distant junction from the reservoir. **Figure 3.3.b** shows that Junction 14 had a maximum time to peak contamination of 39 hours to reach a concentration of 100% with a first order K_b of -0.00027/day. The minimum time to peak contamination was 37 hours to reach a concentration of 99.50% with a first order K_b of -0.07279/day. Junction 20, shown in **Figure 3.3.c**, had a maximum time to peak contamination of 88 hours to reach a concentration of 99.89% with a zero order K_b of -0.38505 µg/L/day. The minimum time to peak contamination was 42 hours to reach a peak concentration of 44.28% with a second order K_b of -0.04350 day*µg/L. Junction 25, seen in **Figure 3.3.d**, had a maximum time to peak contamination of 85 hours to reach 100% with a first order K_b of -0.00027/day. The minimum time to peak contamination was 38 hours to reach 99.90% with a second order K_b of -0.00008. For Junction 14, shown in **Figure 3.3.e**, the maximum time to flush all contamination from the junction was 38 hours for all values of K_b used. Junction 20, shown in Figure **3.3.f**, had a maximum time to flush all contaminants of 45 hours for all K_b except zero order K_b of -0.38505 µg/L/day which required 43 hours to reach 0% contamination. For Junction 25, in **Figure 3.3.g**, the maximum time to flush all contaminant was 40 hours for all K_b except a zero order K_b of -0.38505 µg/L/day which cleared after 38 hours.

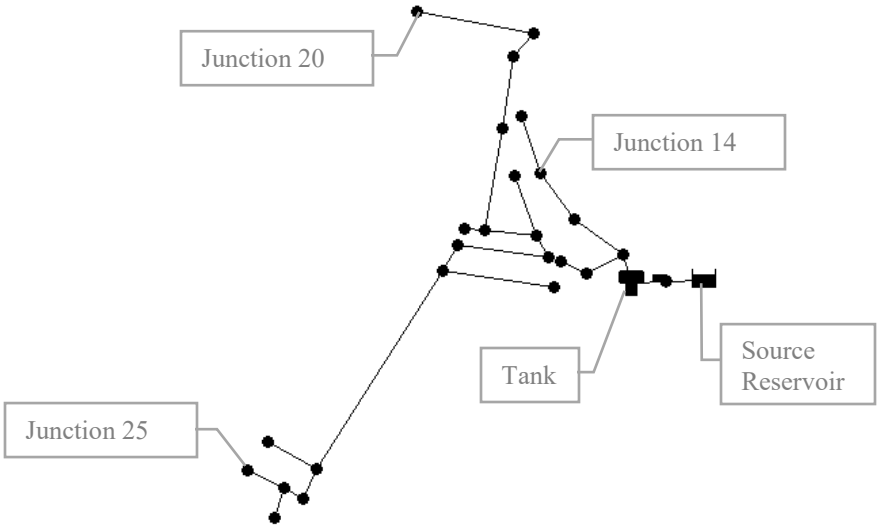

Figure 3.3.a System 3 monitoring junctions.

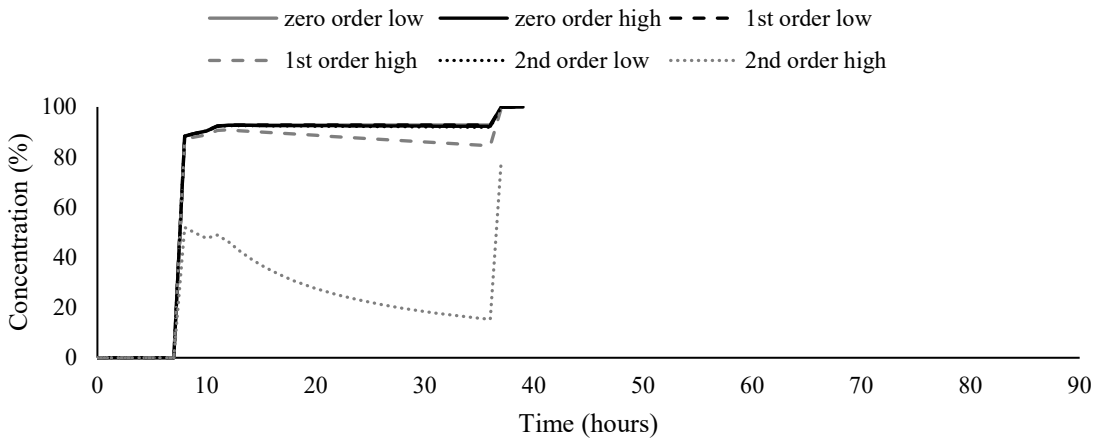

Figure 3.3.b System 3, Junction 14 contaminant spreading history.

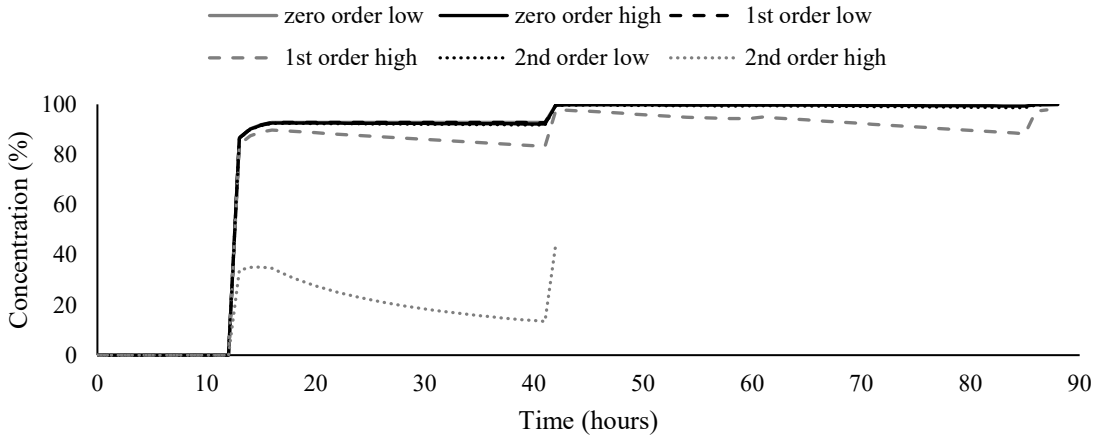

Figure 3.3.c System 3, Junction 20 contaminant spreading history.

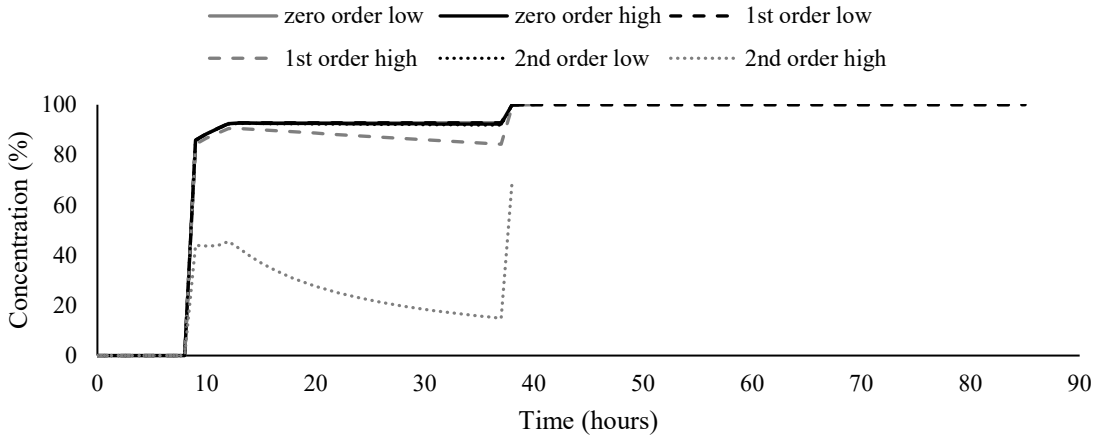

Figure 3.3.d System 3, Junction 25 contaminant spreading history.

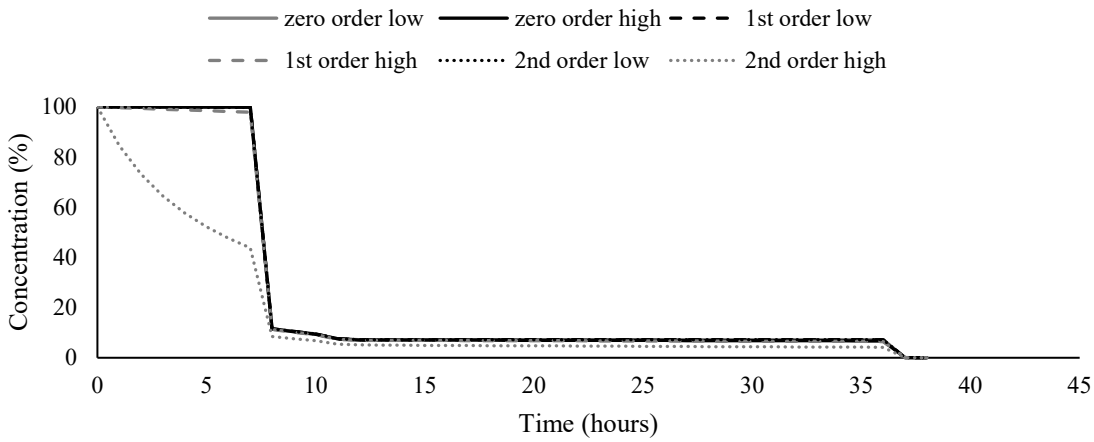

Figure 3.3.e, System 3, Junction 14 contaminant clearing history.

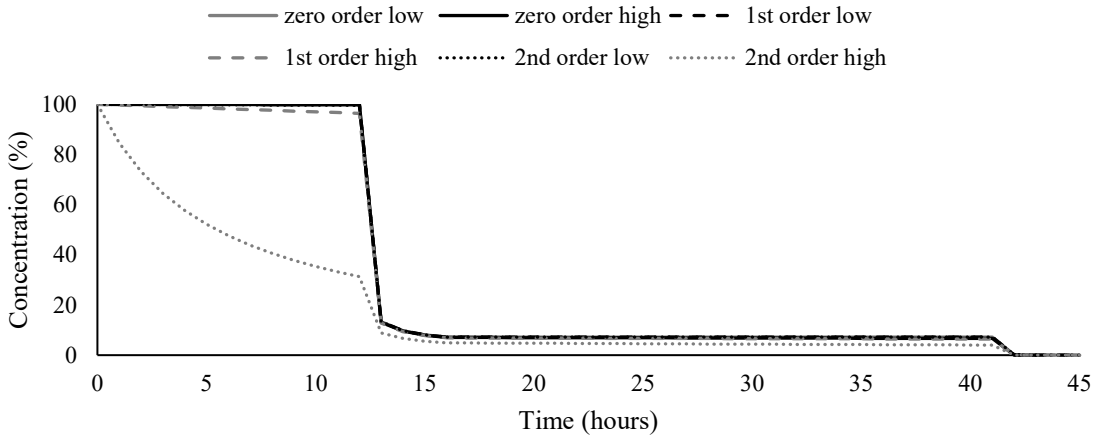

Figure 3.3.f System 3, Junction 20 contaminant clearing history.

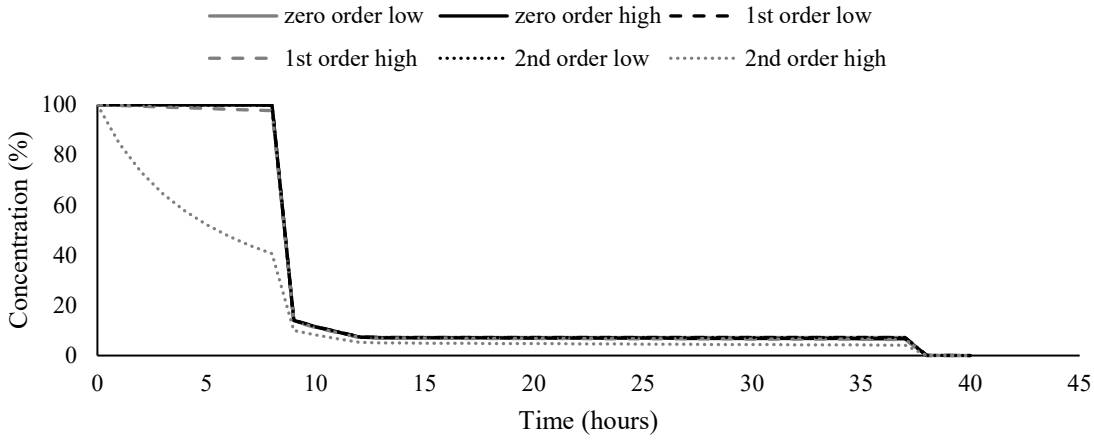

Figure 3.3.g System 3, Junction 25 contaminant clearing history.

System 4 was observed at Junctions 5, 6, and 8 as shown in **Figure 3.1.4.a**. Junction 5 was chosen for observation because it had the longest time to peak contamination, Junction 6 was chosen as a centrally located point, and Junction 8 was chosen as geographically distant from the reservoir. Junction 5, seen in **Figure 3.1.4.b**, had a maximum time to peak contamination of 176 hours to reach a peak concentration of 62.05% with a second order K_b of -0.04350 day*µg/L. The minimum time to peak concentration was 8 hours to reach 100% for both zero order K_b of -0.00055 µg/L/day, and first order K_b of -0.00027/day. For Junction 6, shown in **Figure 3.1.4.c**, the maximum time to peak contamination was 127 hours to reach a peak concentration of 99.06% with a first order K_b of -0.07279/day. The minimum time to peak contamination was 7 hours to reach a concentration of 100% for both zero order K_b of -0.00055 µg/L/day, and first order K_b of -0.00027/day. Junction 8, shown in **Figure 3.1.4.d**, had a maximum time to peak contamination of 172 hours to reach a concentration of 96.35% for a first order K_b of -0.07279/day. The minimum time to peak contamination was 120 hours to reach a peak concentration of 99.47% with a zero order K_b of -0.38505 µg/L/day. Junction 5, shown in **Figure 3.4.e**, had a maximum time to flush all contaminant from the junction of 168 hours for a zero order K_b of -0.00055 µg/L/day, first order K_b of -0.00027/day, and second order K_b of -0.00008 day*µg/L. The minimum time to flush all contaminants was 120 hours for a zero order K_b of -0.38505. For Junction 6, shown in **Figure 3.4.f**, the maximum time to flush all contaminant from the junction was 164 hours for a zero order K_b of -0.00055 µg/L/day, first order K_b of -0.00027/day, and second order K_b of -0.00008 day*µg/L. The minimum time to flush all contaminants was 118 hours for a zero order K_b of -0.38505 µg/L/day. Junction 8, in **Figure 3.4.g**, had a maximum time of 171 hours to reach 0% of the initial concentration for a zero order K_b of -0.00055 µg/L/day, first order K_b of -0.00027/day, and second order K_b of -0.00008 day*µg/L. The minimum time to flush the junction was 121 hours for a zero order K_b of -0.38505 µg/L/day.

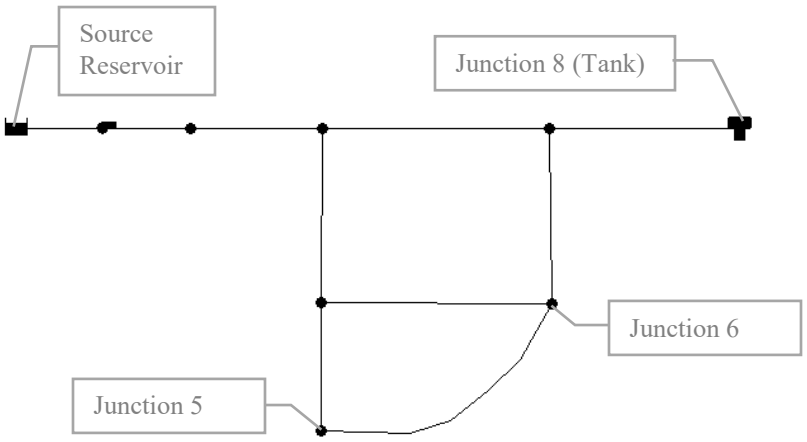

Figure 3.4.a System 4 monitoring junctions.

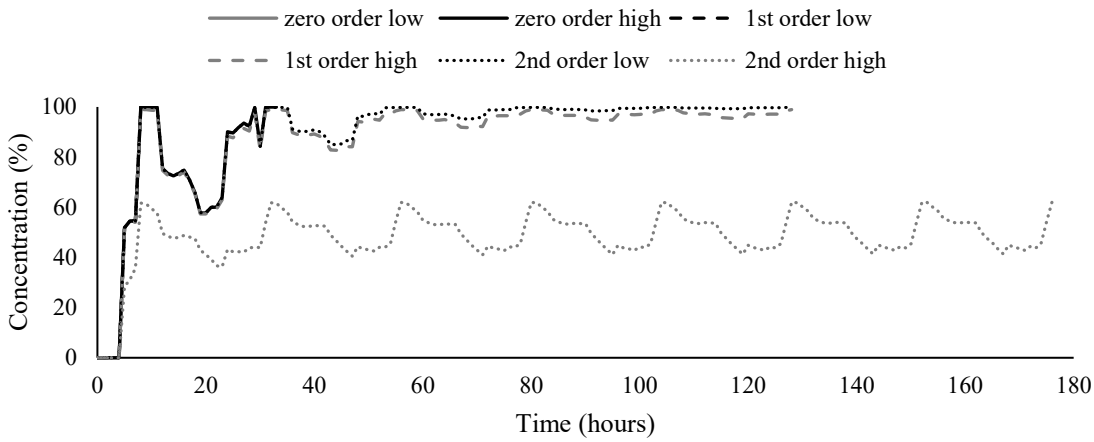

Figure 3.4.b System 4, Junction 5 contaminant spreading history.

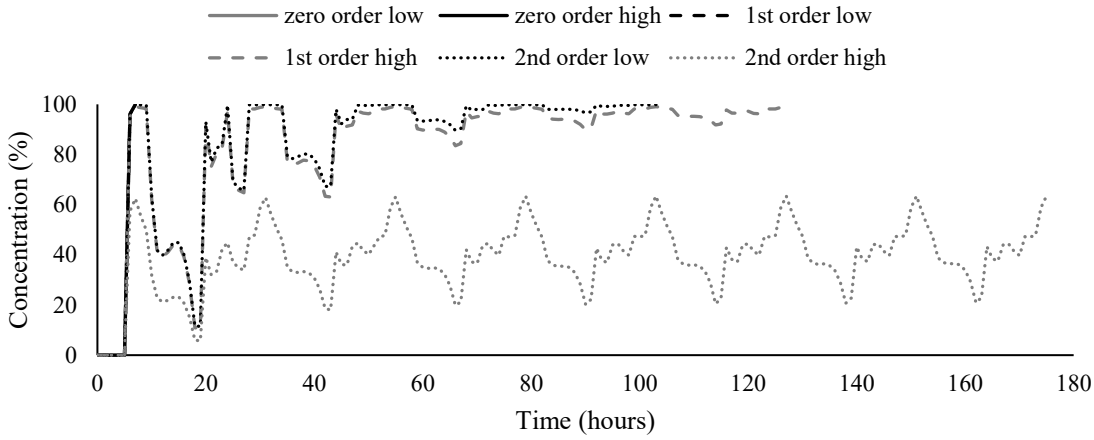

Figure 3.4.c System 4, Junction 6 contaminant spreading history.

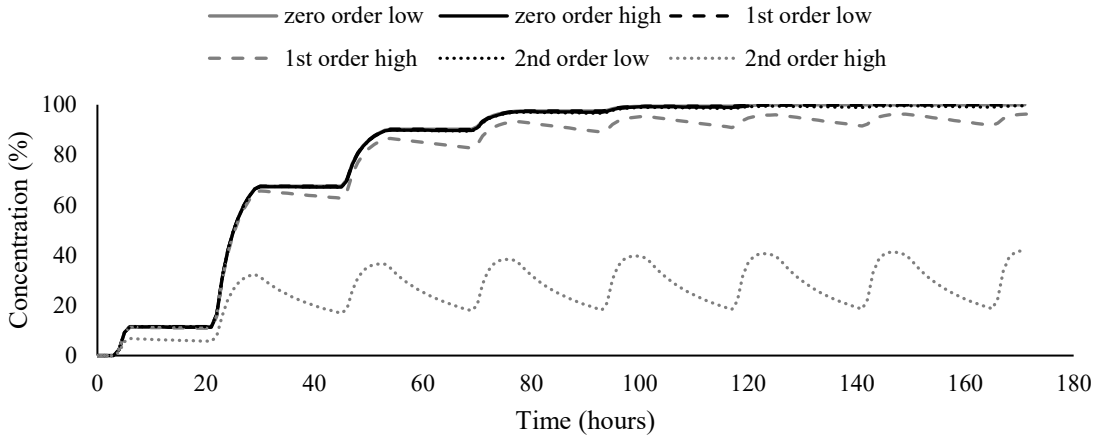

Figure 3.4.d System 4, Junction 8 contaminant spreading history.

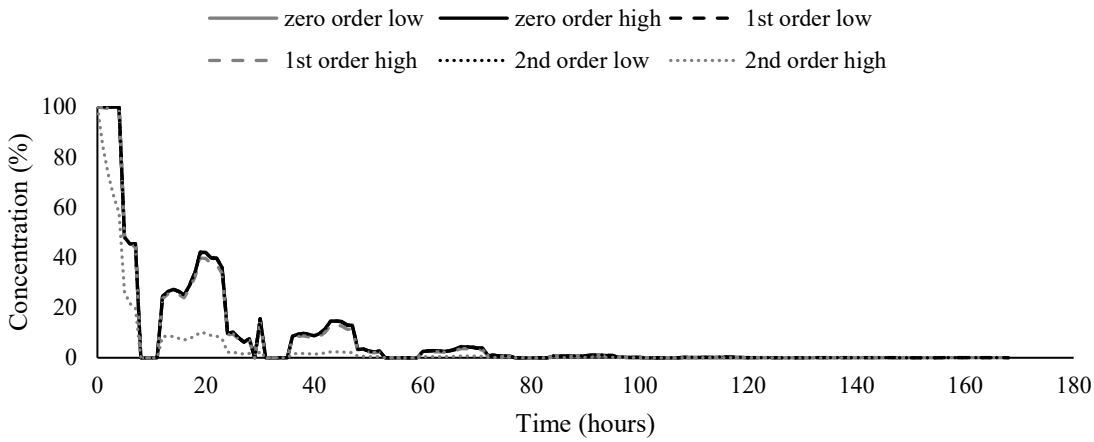

Figure 3.4.e, System 4, Junction 5 contaminant clearing history.

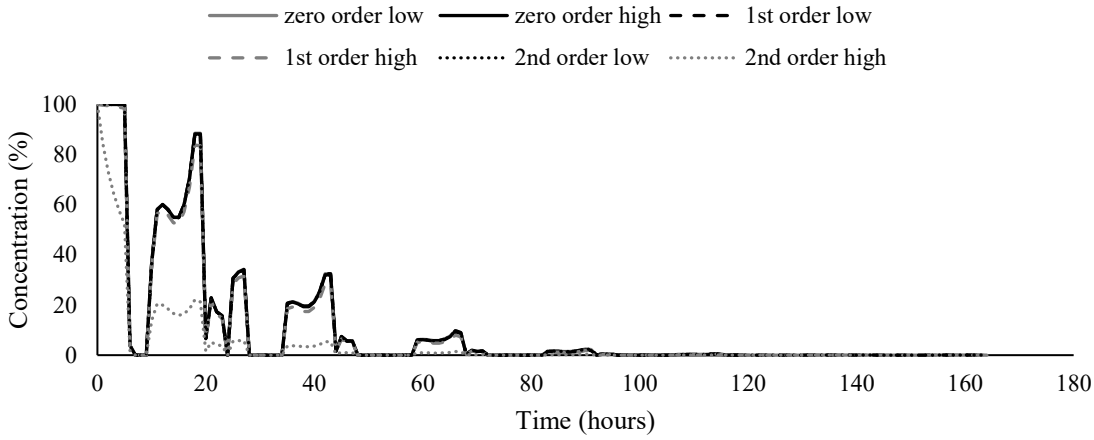

Figure 3.4.f System 4, Junction 6 contaminant clearing history.

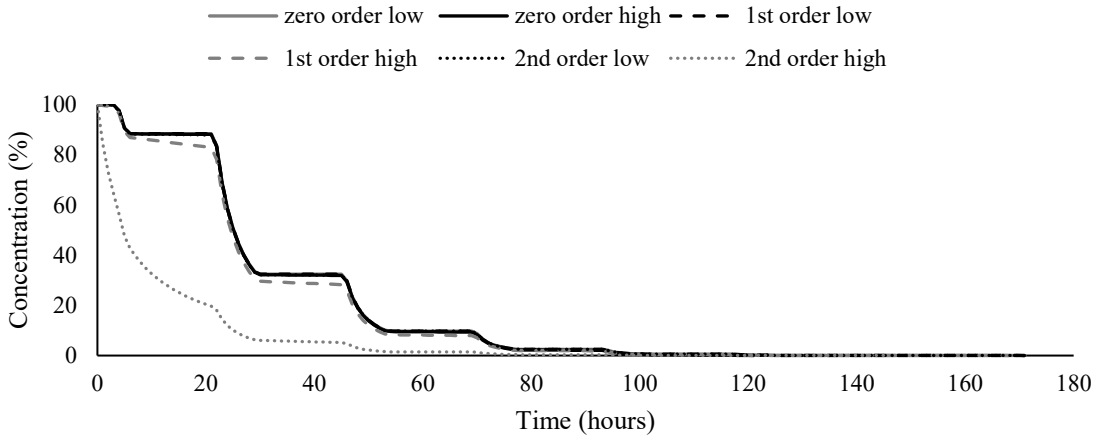

Figure 3.4.g System 4, Junction 8 contaminant clearing history.

System 5, shown in **Figure 3.5.a**, was observed at Junctions 5, 28, and 41. Junction 5 was chosen to observe because it was a centrally located point, Junction 28 was chosen to observe as a geographically distant point, and Junction 41 was chosen as the longest time to reach peak contamination. Junction 5, shown in **Figure 3.5.b**, had a maximum time to peak contamination of 134 hours to reach 94.15% with a second order K_b of -0.04350 day*µg/L. The minimum time to peak contamination was 12 hours to reach 100% contamination for a zero order K_b of -0.00055 µg/L/day, and first order K_b of -0.00027/day. Junction 28, in **Figure 3.5.c**, had a maximum time to peak contamination of 201 hours to reach 92.10% with a second order K_b of -0.04350 day*µg/L. The minimum time to peak contamination was 7 hours to reach 100% for a zero order K_b of -0.00055 µg/L/day, and a first order K_b of -0.00027/day. For Junction 41, shown in **Figure 3.5.d**, the maximum time to peak contamination was 211 hours to reach a concentration of 99.10% with a first order K_b of -0.07279/day. The minimum time to peak contamination was 10 hours to reach 100% for both a zero order K_b of -0.00055 µg/L/day, and a first order K_b of -0.00027/day. For Junction 5, seen in **Figure 3.5.e**, the maximum time to flush the contaminant from the system was 348 hours for a zero order K_b of -0.00055 µg/L/day, first order K_b of -0.00027/day, and second order K_b of -0.00008 day*µg/L. The minimum time to flush all contaminants was 170 hours for a zero order K_b of -0.38505 µg/L/day. Junction 28, in **Figure 3.5.f**, had a maximum time to flush all contaminant from the junction of 331 hours for all K_b except zero order K_b of -0.38505 µg/L/day, and second order K_b of -0.04054 day*µg/L. The minimum time needed was 172 hours for a zero order K_b of -0.38505 µg/L/day. **In Figure 3.5.g**, Junction 41 had a maximum time to reach 0% of the initial contaminant of 336 hours for all K_b used except zero order K_b of -0.38505 µg/L/day, and second order K_b of -0.04350 day*µg/L. The minimum time to flush the junction was 172 hours for a zero order K_b of -0.38505 µg/L/day.

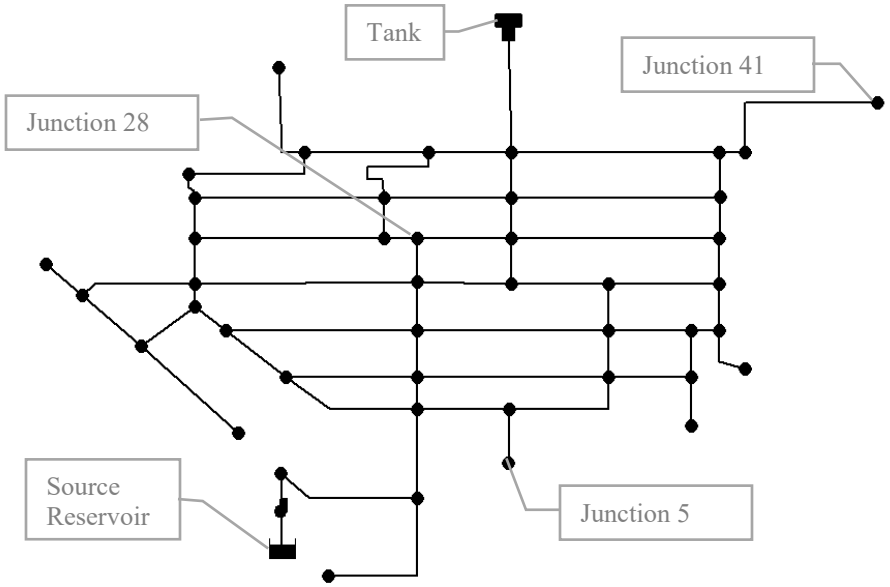

Figure 3.5.a System 5 monitoring junctions.

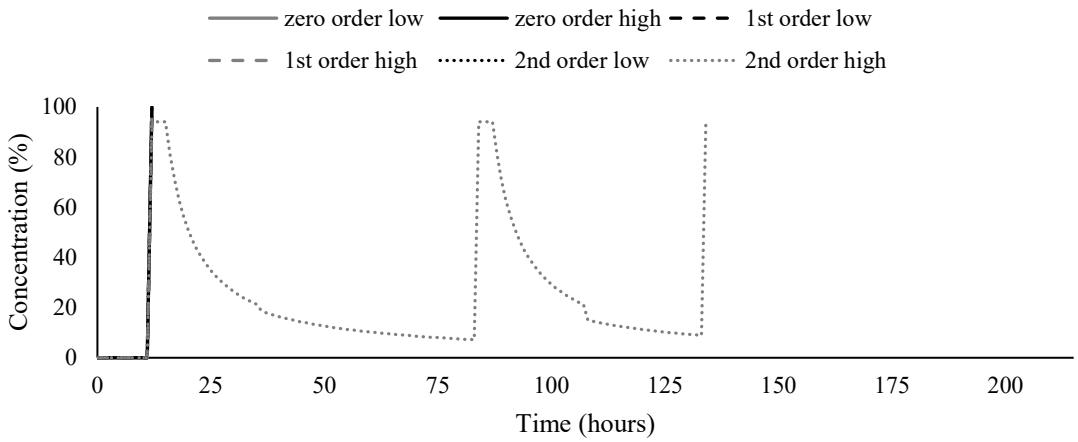

Figure 3.5.b System 5, Junction 5 contaminant spreading history.

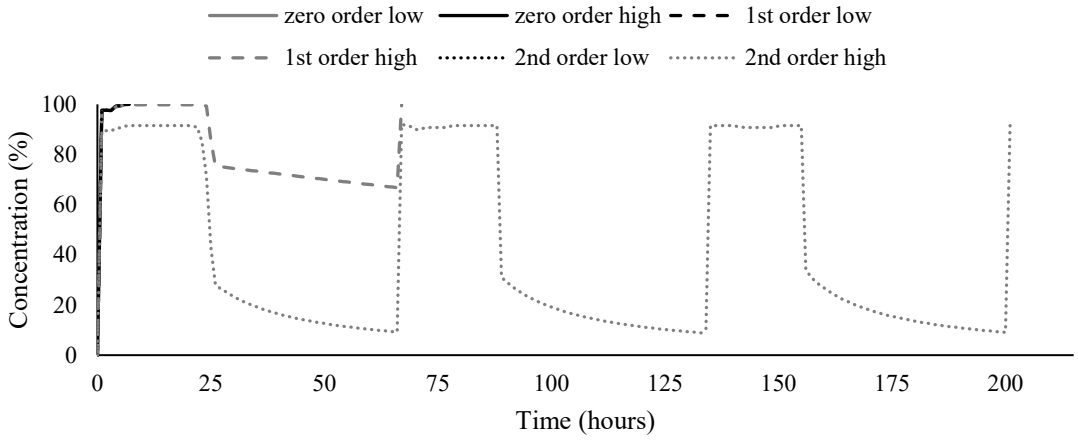

Figure 3.5.c System 5, Junction 28 contaminant spreading history.

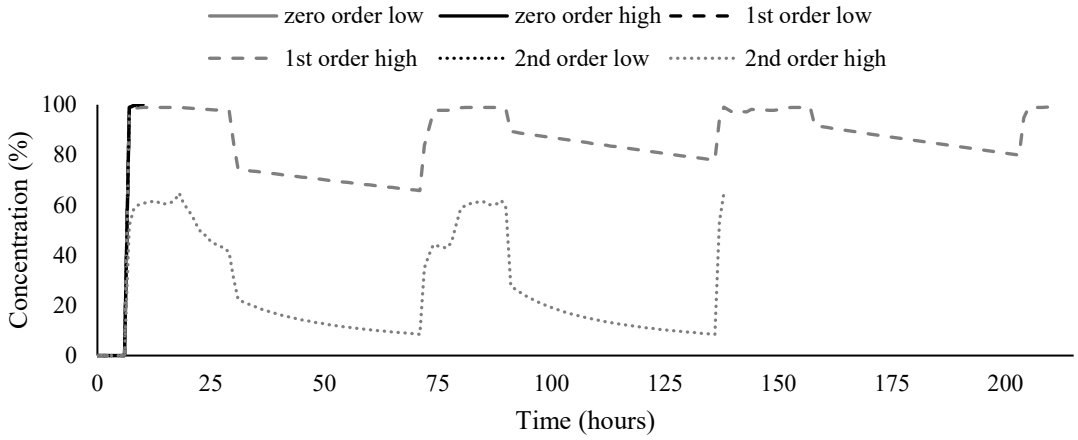

Figure 3.5.d System 5, Junction 41 contaminant spreading history.

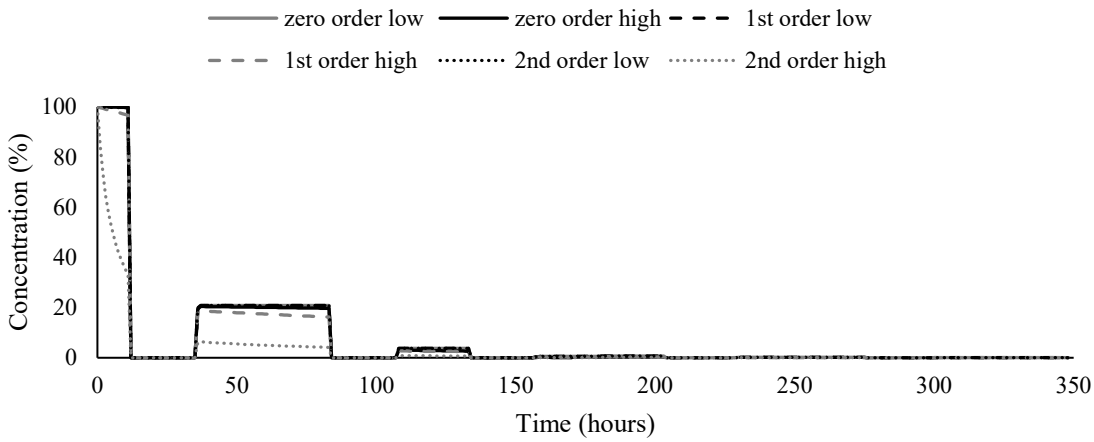

Figure 3.5.e System 5, Junction 5 contaminant clearing history.

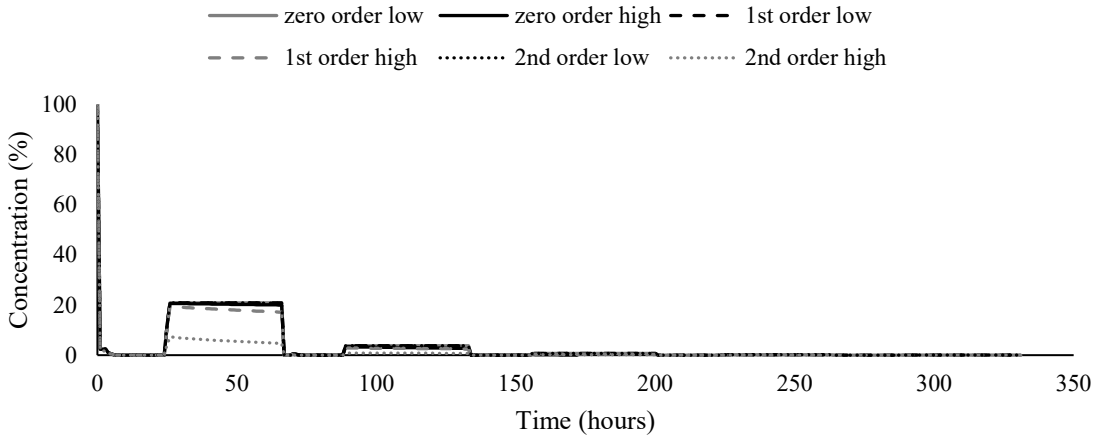

Figure 3.5.f System 5, Junction 28 contaminant clearing history.

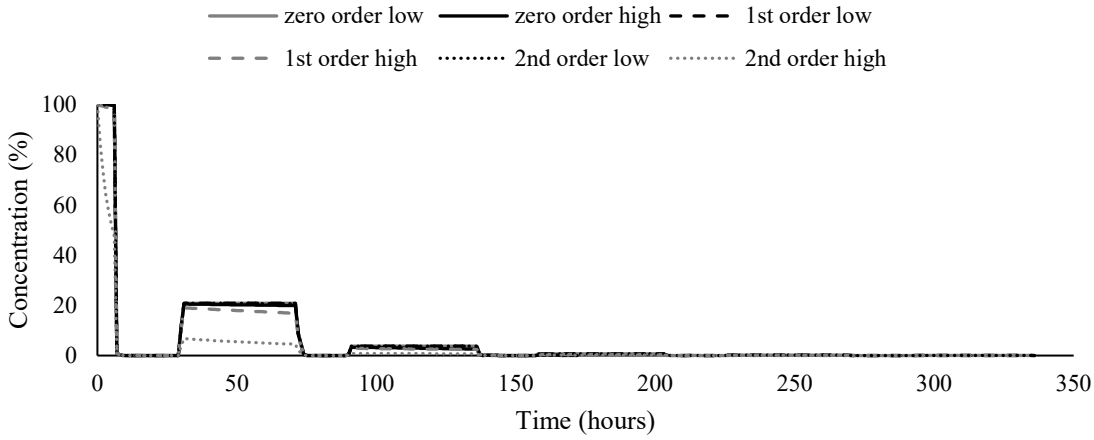

Figure 3.5.g System 5, Junction 41 contaminant clearing history.

System 6, shown in **Figure 3.6.a**, was observed at Junctions 11, 57, and 102. Junction 11 was chosen for observation because it was a geographically distant junction from the reservoir, Junction 57 was observed because it was located centrally in the system, and Junction 102 was chosen as the longest time to reach peak contamination. Junction 11, seen in **Figure 3.6.b**, had a maximum time to peak contamination of 154 hours to reach 10.55% with a second order K_b of -0.04350 day*µg/L. The minimum time to reach peak contamination was 80 hours to reach 86.46% with a first order K_b of -0.07279/day. Junction 57, in **Figure 3.6.c**, had a maximum time to peak contamination of 33 hours to reach a concentration of 99.90% with a zero order K_b of -0.38505 µg/L/day. The minimum time to peak contamination was 29 hours to reach 100% for a zero order K_b of -0.00055 µg/L/day. For junction 102, shown in **Figure 3.6.d**, the maximum time to peak contamination was 421 hours to reach a maximum concentration of 99.98% with a zero order K_b of -0.00055 µg/L/day. The minimum time to peak contamination was 31 hours to reach 98.26% with a first order K_b of -0.07279 µg/L/day. In **Figure 3.6.e**, Junction 11 had a maximum time needed to flush the junction of 1017 hours for a first order K_b of -0.00027. The minimum time to flush the junction was 437 hours for a zero order Kb of -0.38505/day. For Junction 57, seen in **Figure 3.6.f**, the maximum time to flush the junction was 995 hours for a first order K_b of -0.00027/day. The minimum time to flush the contaminant from Junction 57 was 435 hours for a zero order K_b of -0.38505 µg/L/day. Junction 102, shown in **Figure 3.6.g**, had a maximum time to flush the contaminant of 1,591 hours for a first order K_b of -0.00027/day and second order K_b of -0.00008 day*µg/L. The minimum time needed for Junction 102 was 656 hours for a zero order K_b of -0.38505 µg/L/day.

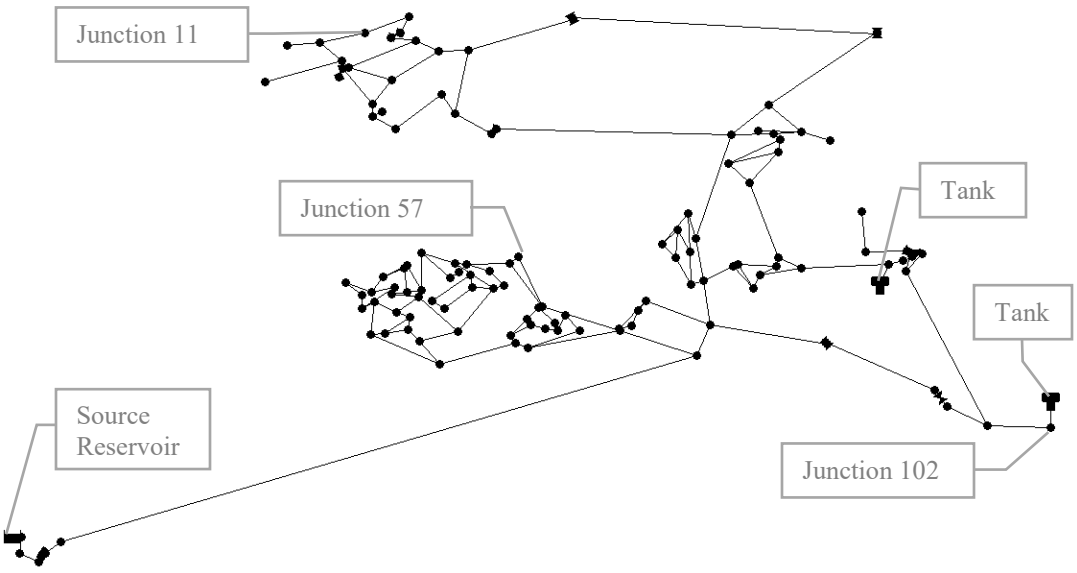

Figure 3.6.a System 6 monitoring junctions.

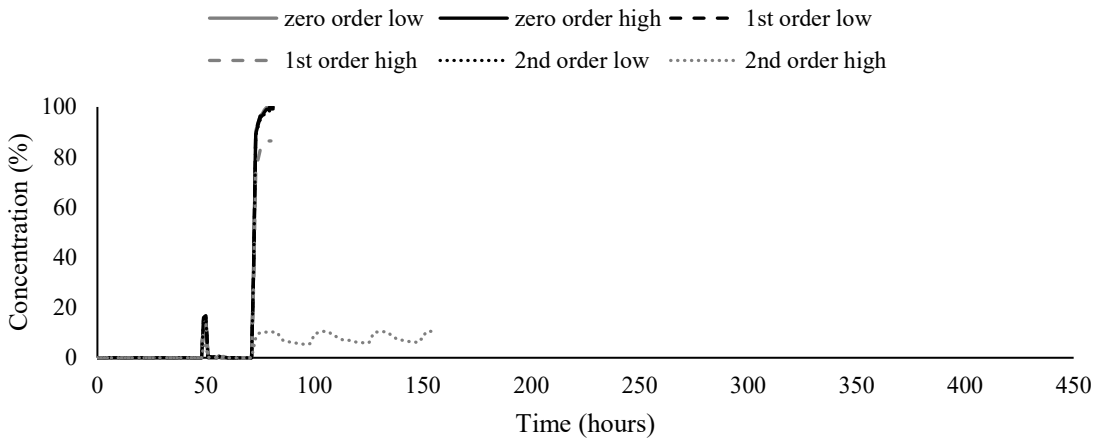

Figure 3.6.b System 6, Junction 11 contaminant spreading history.

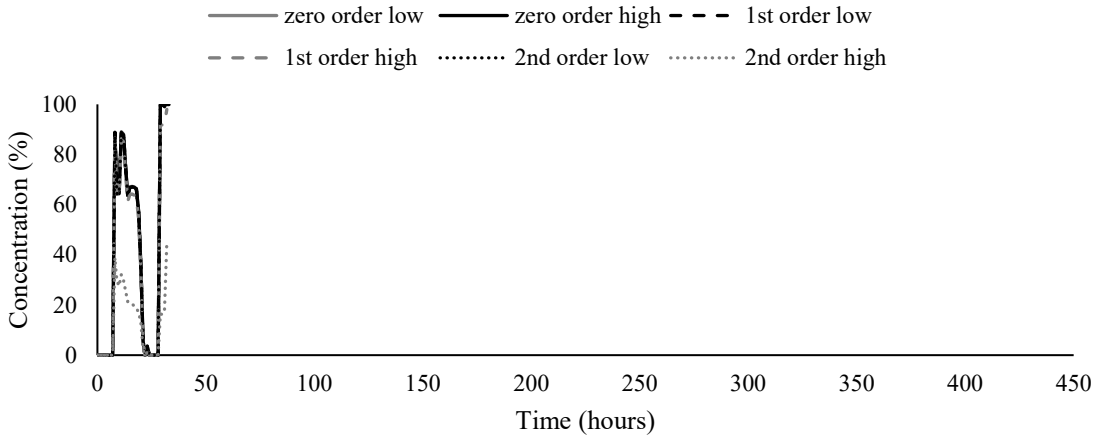

Figure 3.6.c System 6, Junction 57 contaminant spreading history.

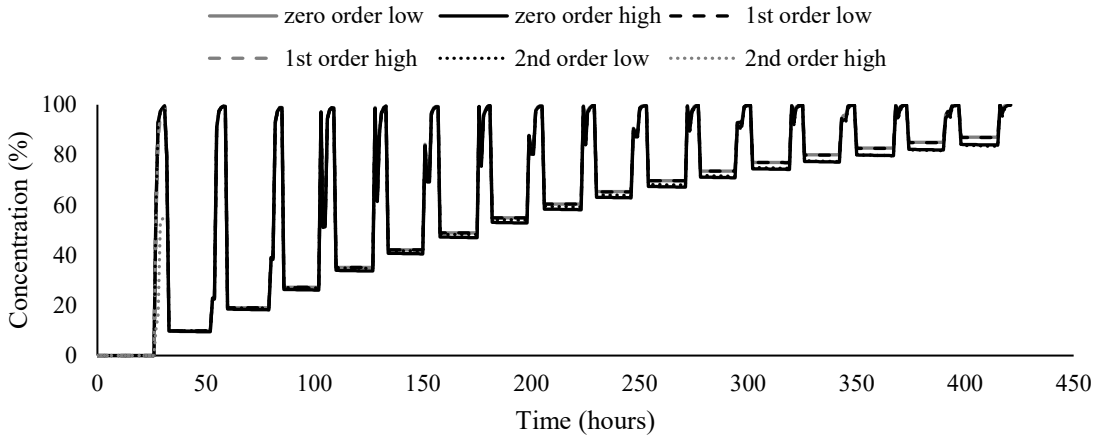

Figure 3.6.d System 6, Junction 102 contaminant spreading history.

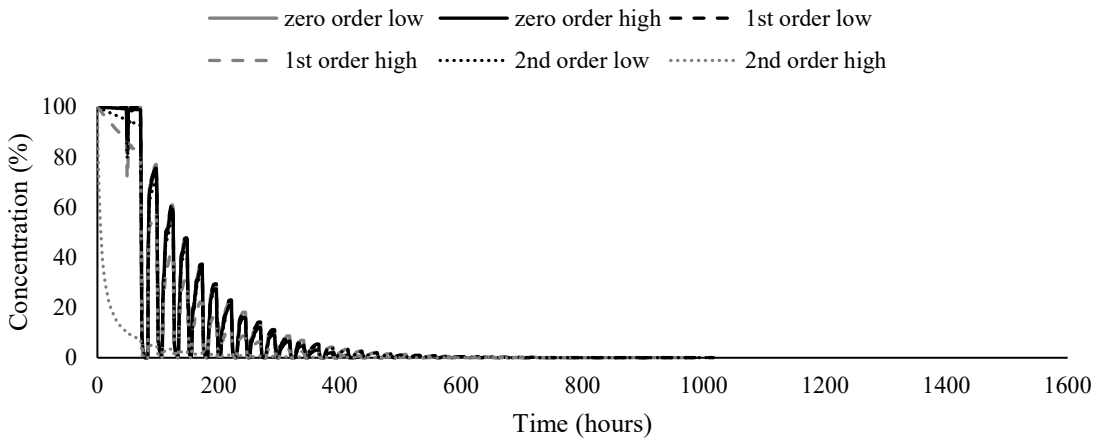

Figure 3.6.e System 6, Junction 11 contaminant clearing history.

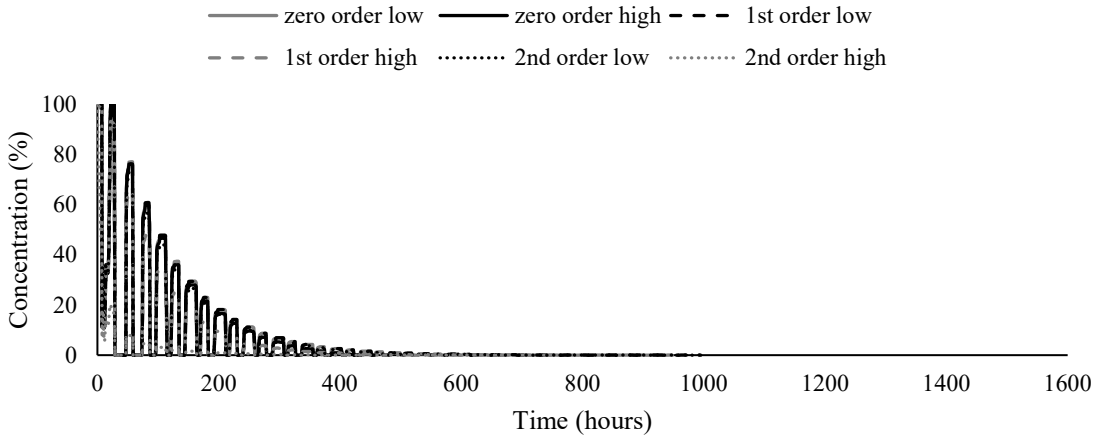

Figure 3.6.f System 6, Junction 57 contaminant clearing history.

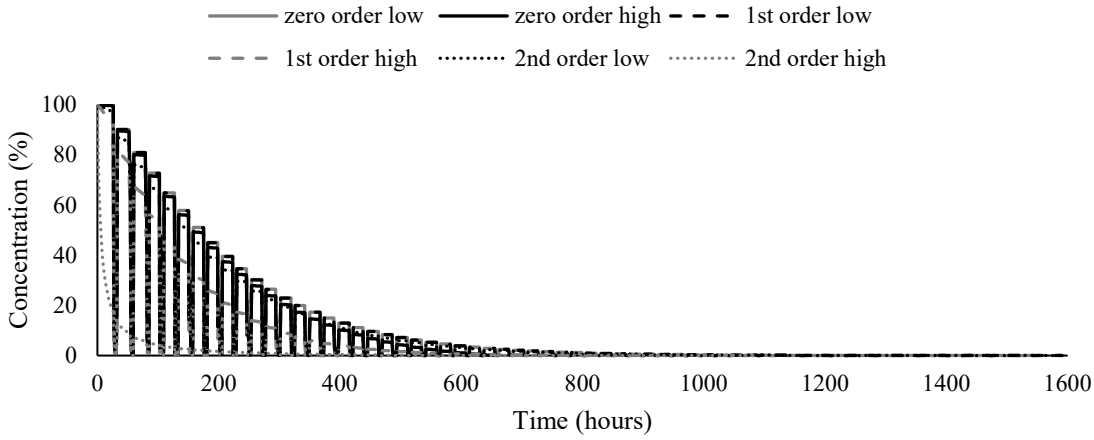

Figure 3.6.g System 6, Junction 102 contaminant clearing history.

System 7, shown in **Figure 3.1.7.a**, was observed at Junctions 450, 1050, and 1080. Junction 450 was observed due having the longest time to reach peak contamination, Junction 1050 was chosen because it was geographically distant from the source, and Junction 1080 was chosen because it was centrally located in the system. Junction 450, seen in **Figure 3.1.7.b**, had a maximum time to peak contamination of 253 hours to reach 98.23% of the source contamination level with a first order K_b of -0.07279/day. The minimum time to peak contamination was 16 hours to reach a peak concentration of 61.44% with a second order K_b of -0.04350 day*µg/L. Junction 1050, in **Figure 3.7.c**, reached peak contamination in 18 hours for all values K_b used with a maximum concentration of 100% for a zero order K_b of -0.00055 µg/L/day. For Junction 1080, shown in **Figure 3.7.d**, the maximum time to peak contamination was 20 hours to reach a concentration of 99.86% with a zero order K_b of -0.38505 µg/L/day, and the minimum time to peak contamination was 12 hours to reach 100% for a zero order K_b of -0.00055 µg/L/day. Junction 450, in **Figure 3.7.e**, had a maximum time to flush the contamination of the junction of 259 hours for a zero order K_b of -0.00055 µg/L/day, first order K_b of -0.00027/day, and second order K_b of -0.00008 day*µg/L. The minimum time to clear Junction 450 of contamination was 148 hours for a zero order K_b of -0.38505 µg/L/day. For Junction 1050, in **Figure 3.7.f**, the maximum time to clear the contamination was 267 hours for a first order K_b of -0.00027/day and second order K_b of -0.00008 day*µg/L, and the minimum time to flush the contamination from Junction 1050 was 154 hours with a zero order K_b of -0.38505 µg/L/day. Junction 1080, shown in **Figure 3.7.g**, had a maximum time to flush the contamination of 276 hours for a first order K_b of -0.00027/day and second order K_b of -0.00008 day*µg/L. The minimum time needed to reach 0% concentration of contaminants in Junction 1080 was 152 hours for a zero order K_b of -0.38505 µg/L/day.

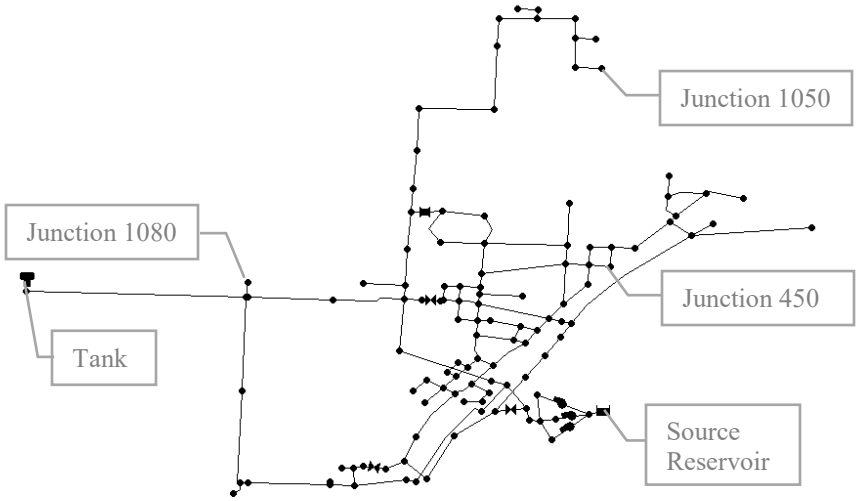

Figure 3.7.a System 7 monitoring junctions.

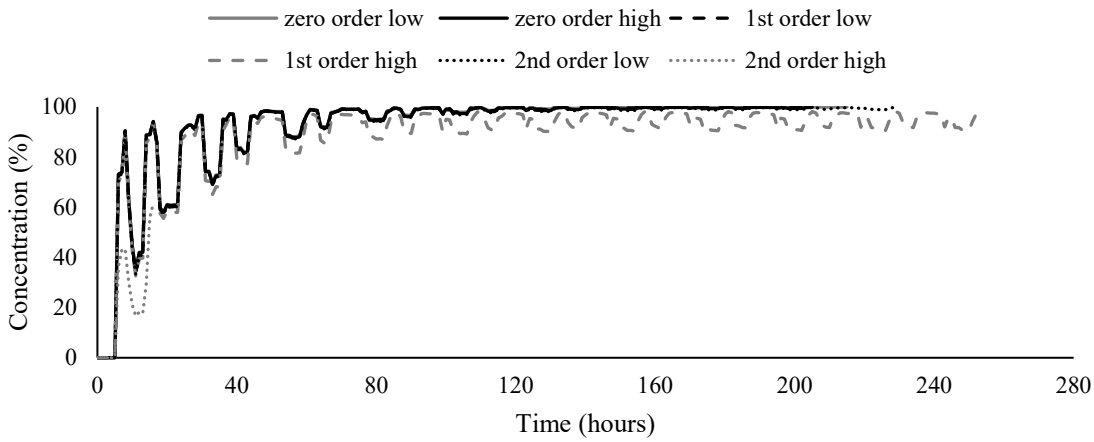

Figure 3.7.b system 7, Junction 450 contaminant spreading history.

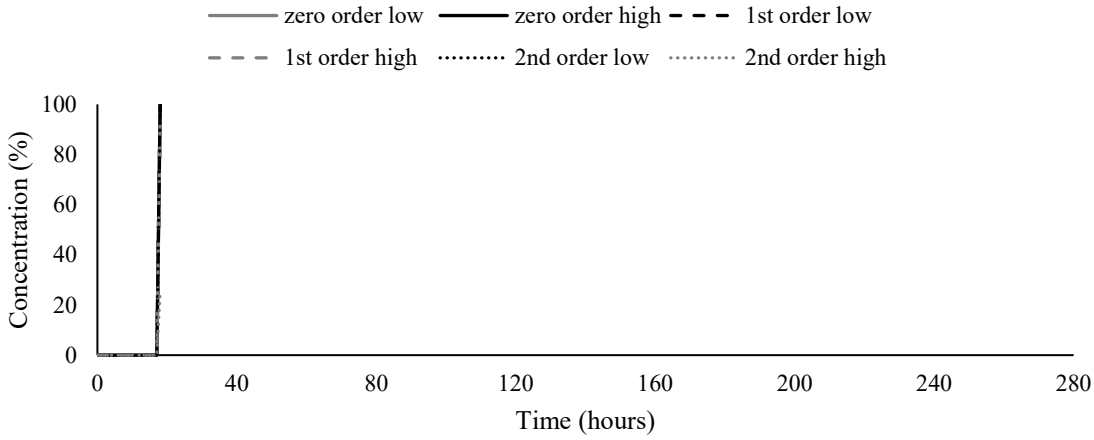

Figure 3.7.c System 7, Junction 1050 contaminant spreading history.

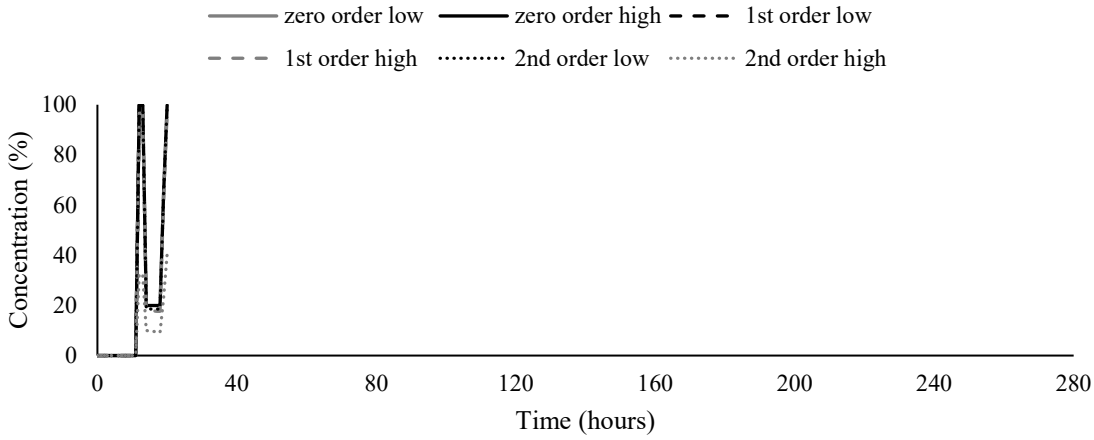

Figure 3.7.d System 7, Junction 1080 contaminant spreading history.

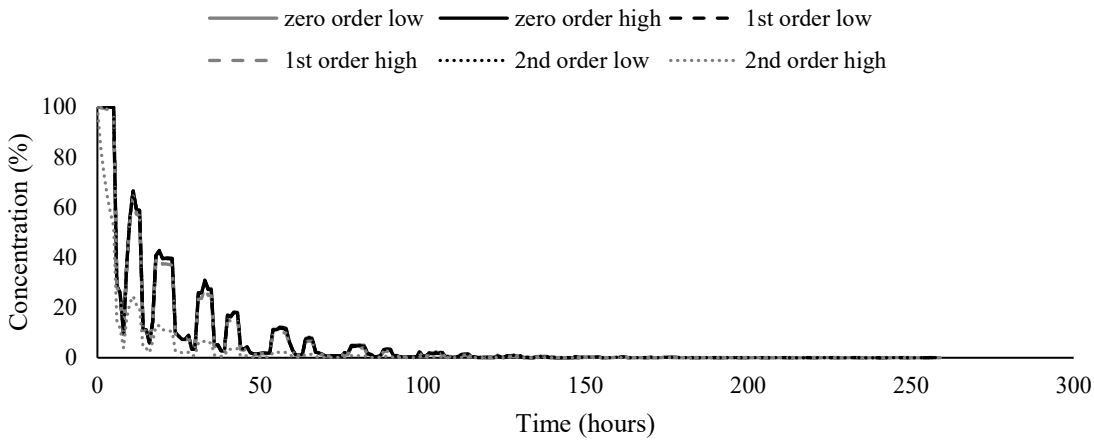

Figure 3.7.e System 7, Junction 450 contaminant clearing history.

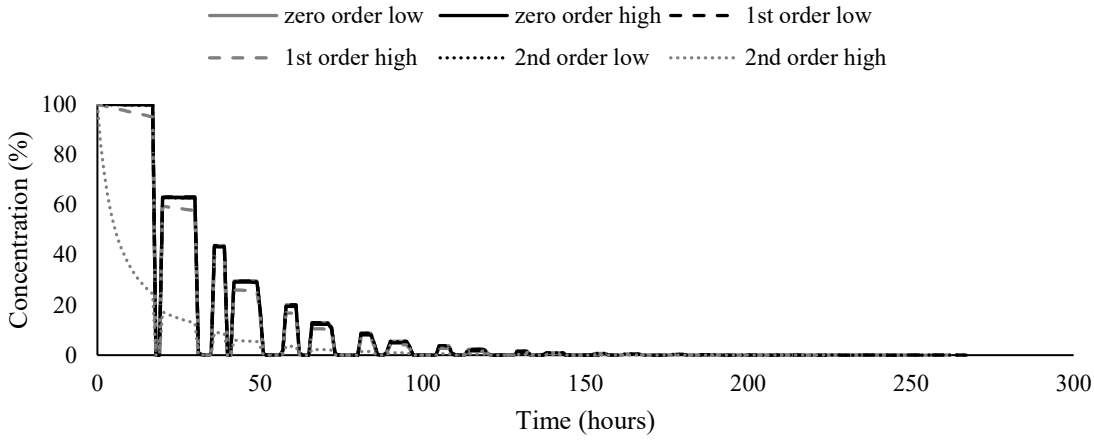

Figure 3.7.f System 7, Junction 1050 contaminant clearing history.

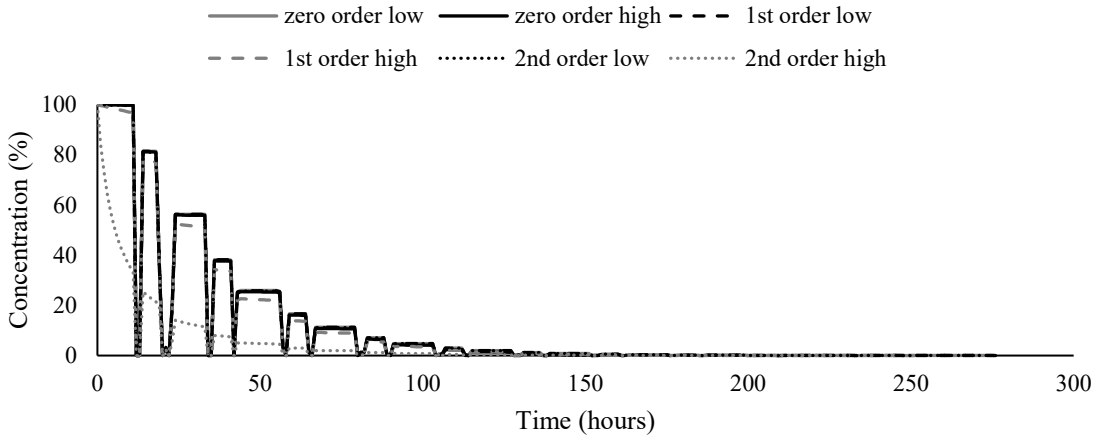

Figure 3.7.g System 7, Junction 1080 contaminant clearing history.

System 8, shown in **Figure 3.8.a**, was observed at Junctions 82, 218, and 318. Junction 82 was chosen for observation because it had the longest time to peak contamination, Junction 218 was chosen because it was a centrally located junction, and Junction 318 was chosen because it was geographically distant from the source. For Junction 82, shown in **Figure 3.8.b**, the maximum time to reach peak contamination was 473 hours to reach a concentration of 99.99% with a zero order K_b of -0.00055 µg/L/day. The minimum time to peak contamination for Junction 82 was 331 hours to reach a concentration of 1.65% with a second order K_b of -0.04350 day*µg/L. Junction 218, shown in **Figure 3.8.c**, had a maximum time to peak contamination of 389 minutes to reach 97.04% with a zero order K_b of -0.00055 µg/L/day. The minimum time to peak contamination was 116 hours to reach a concentration of 5.25% with a second order K_b of -0.04350 day*µg/L. For Junction 318, shown in **Figure 3.8.d**, the maximum time to peak contamination was 159 hours to reach a concentration of 95.38% with a first order K_b of -0.07279/day. The minimum time to reach peak contamination was 63 hours to reach 100% of the source contamination level with a zero order K_b of -0.00055 µg/L/day. The maximum time needed to flush the contaminant from Junction 82, shown in **Figure 3.8.e**, was 994 hours for first order K_b of -0.00027/day, and second order K_b's of -0.00008 day*µg/L and -0.04350 day*µg/L. The minimum time needed to clear the contaminant from Junction 82 was 376 hours for a zero order K_b of -0.38505 µg/L/day. For Junction 218, in **Figure 3.8.f**, the maximum time needed to flush the contaminant from the junction was 852 hours for a zero order K_b of -0.00055 µg/L/day, a first order K_b of -0.00027/day, and a second order K_b of -0.00008 day*µg/L. The minimum time needed to clear Junction 218 was 802 hours for a zero order K_b of -0.38505 µg/L/day. Junction 318, shown in **Figure 3.8.g**, had a maximum time to flush the contaminant of 972 hours for first order K_b's of -0.00027/day, and second order K_b's of -0.00008 day*µg/L and -0.04350 day*µg/L.

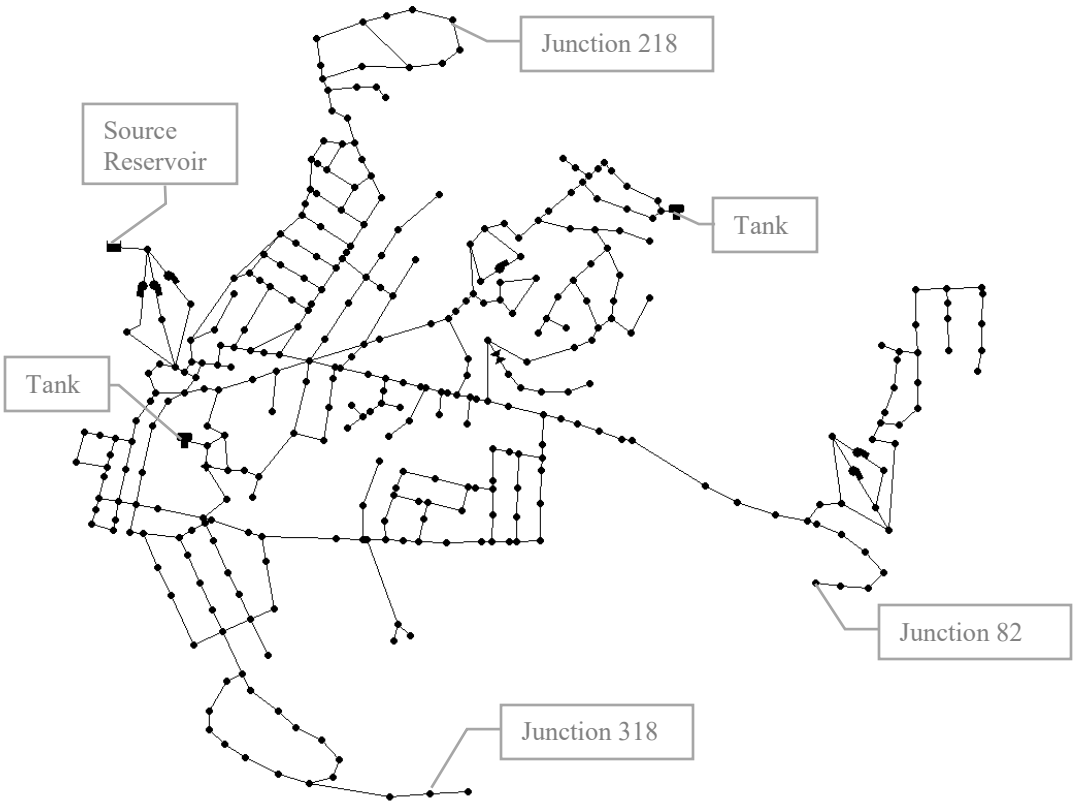

Figure 3.8.a System 8 monitoring junctions.

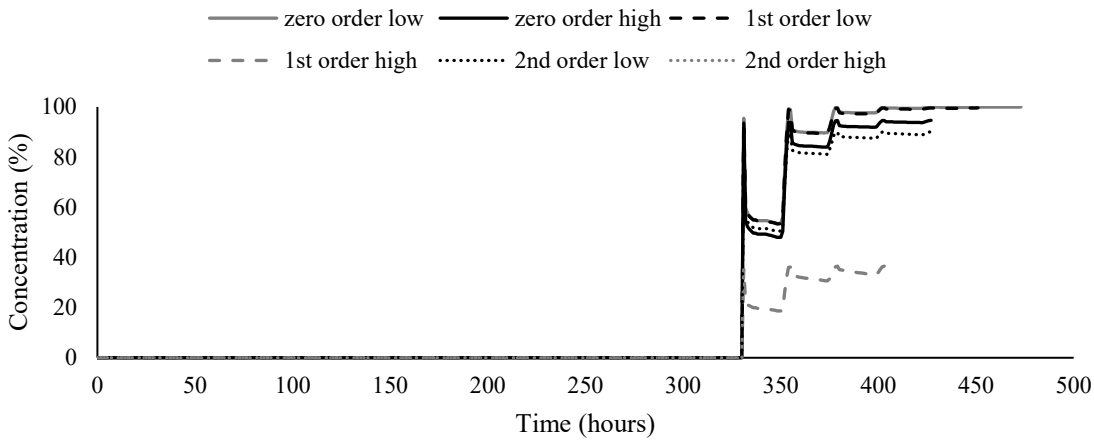

Figure 3.8.b System 8, Junction 82 contaminant spreading history.

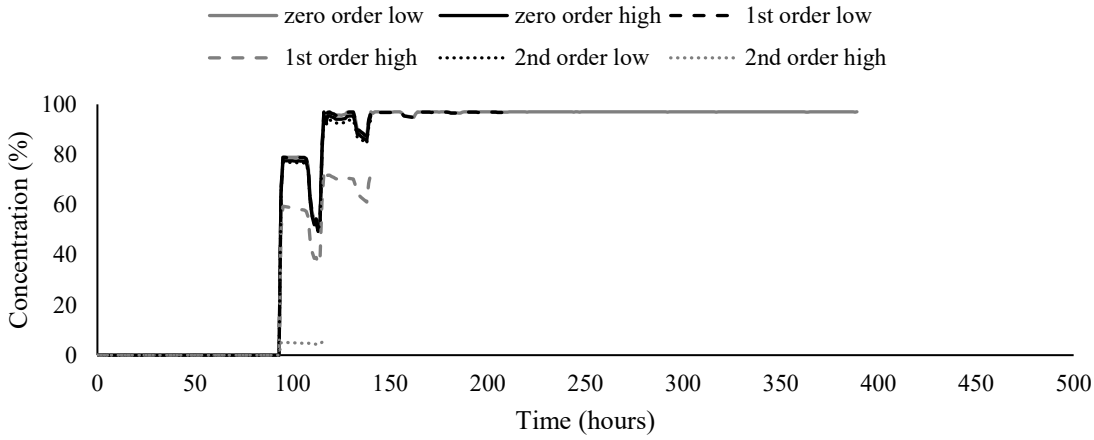

Figure 3.8.c System 8, Junction 218 contaminant spreading history.

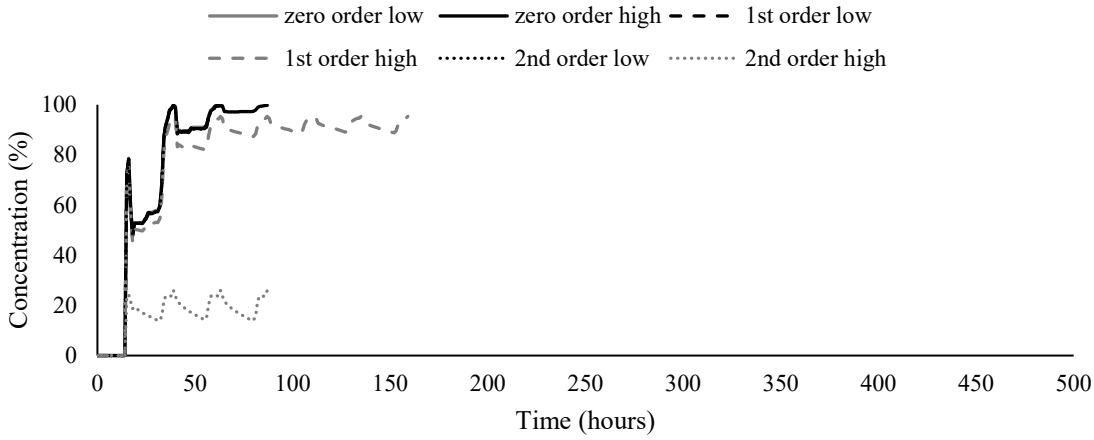

Figure 3.8.d System 8, Junction 318 contaminant spreading history.

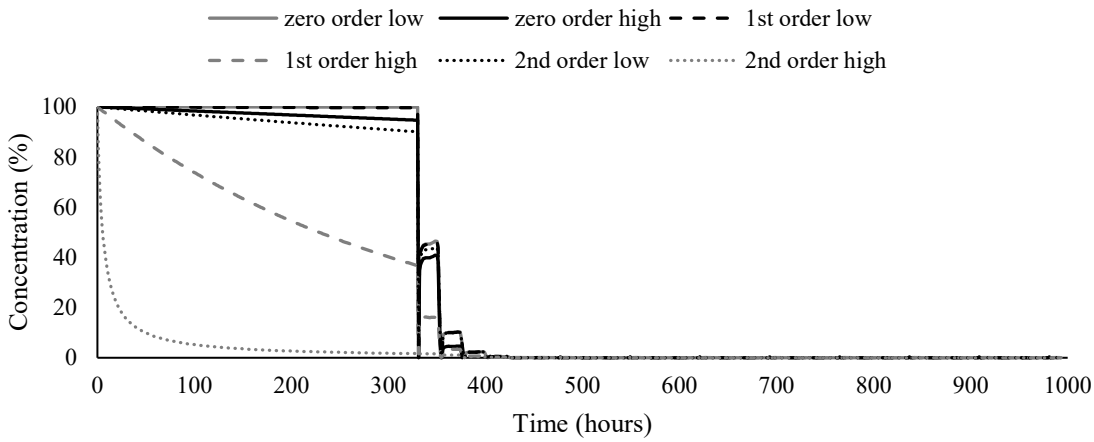

Figure 3.8.e System 8, Junction 82 contaminant clearing history.

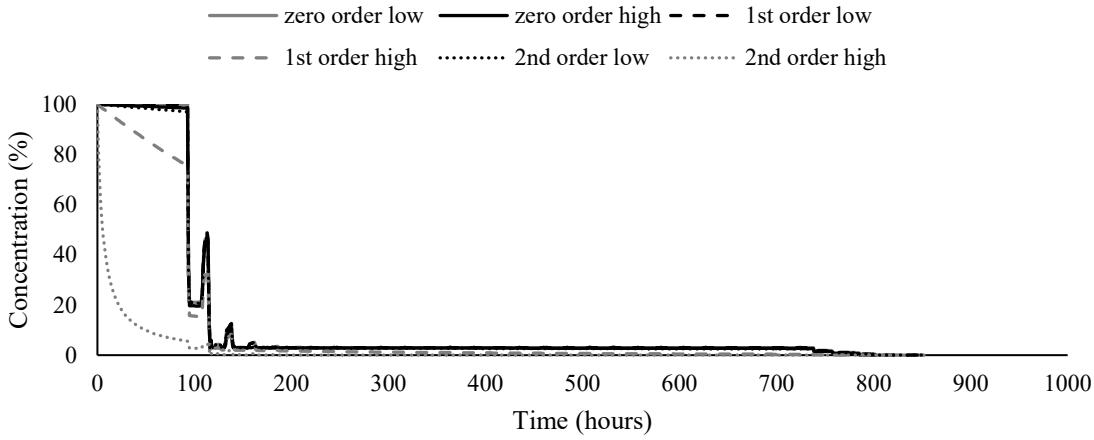

Figure 3.8.f System 8, Junction 218 contaminant clearing history.

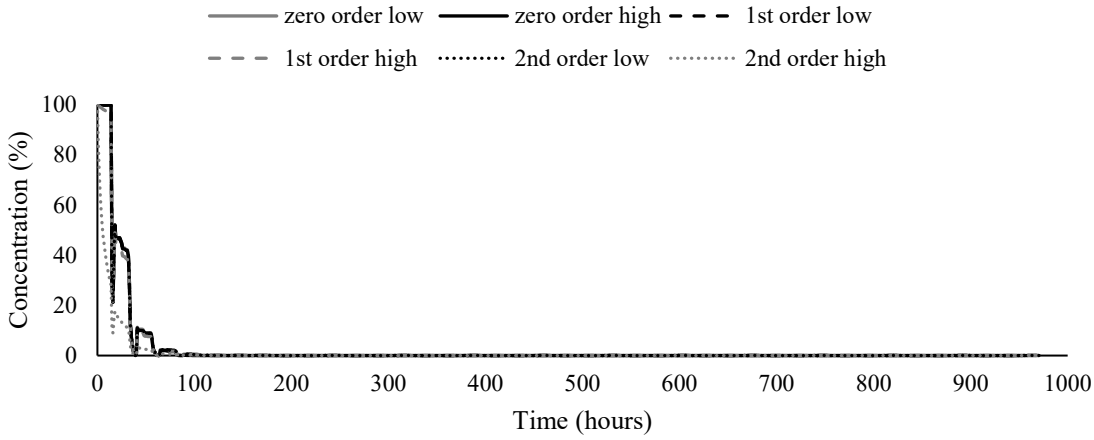

Figure 3.8.g System 8, Junction 318 contaminant clearing history.

System 9, shown in **Figure 3.9.a**, was observed at Junctions 383, 814, and 862. Junction 383 was chosen for observation because it was geographically distant from the source, Junction 814 was chosen because it was located centrally in the system, and Junction 862 was observed because it had to longest time to peak contamination. For Junction 383, shown in **Figure 3.9.b**, the maximum time to reach peak contamination was 68 hours to reach a concentration of 99.38% with a zero order K_b of -0.38505 µg/L/day. The minimum time to peak contamination was 60 hours to reach 100% of the source contamination levels with a zero order K_b of -0.00055 µg/L/day. In **Figure 3.9.c**, the maximum time to peak contamination at Junction 814 was 136 hours to reach 92.11% with a first order K_b of -0.07279/day, and the minimum time to reach peak contamination was 112 hours to reach a peak of 100% of the source contamination levels with a zero order K_b of -0.04054 µg/L/day. Junction 862, shown in **Figure 3.9.d**, had a maximum time to peak contamination of 116 hours to reach 98.80% with a zero order K_b of -0.38505 µg/L/day. The minimum time to peak contamination was 112 hours to reach a maximum concentration of 99.92% with a first order K_b of -0.00027/day. For Junction 383, in **Figure 3.9.e**, the maximum time to clear the contaminant from the junction was 60 hours for all values of K_b except for a zero order K_b of -0.38505 µg/L/day which took 56 hours to clear, and second order K_b of -0.04350 day*µg/L, which took 59 hours. Junction 814, shown in **Figure 3.9.f**, had a maximum time to flush the contaminant of 112 hours for a zero order K_b of -0.00055 µg/L/day, first order K_b's of -0.00027/day and -0.07279/day, and second order K_b of -0.00008 day*µg/L. The minimum time to reach 0% of the initial contamination in Junction 814 was 103 hours with a zero order Kb of -0.38505 µg/L/day. For Junction 862, in **Figure 3.9.g**, the maximum time needed to flush the contamination from the junction was 111 hours for a zero order K_b of -0.00055 µg/L/day, first order K_b of -0.00027/day, and second order K_b of -0.00008 day*µg/L. The minimum time needed to clear the junction of contaminant was 106 hours for a zero order K_b of -0.38505 µg/L/day.

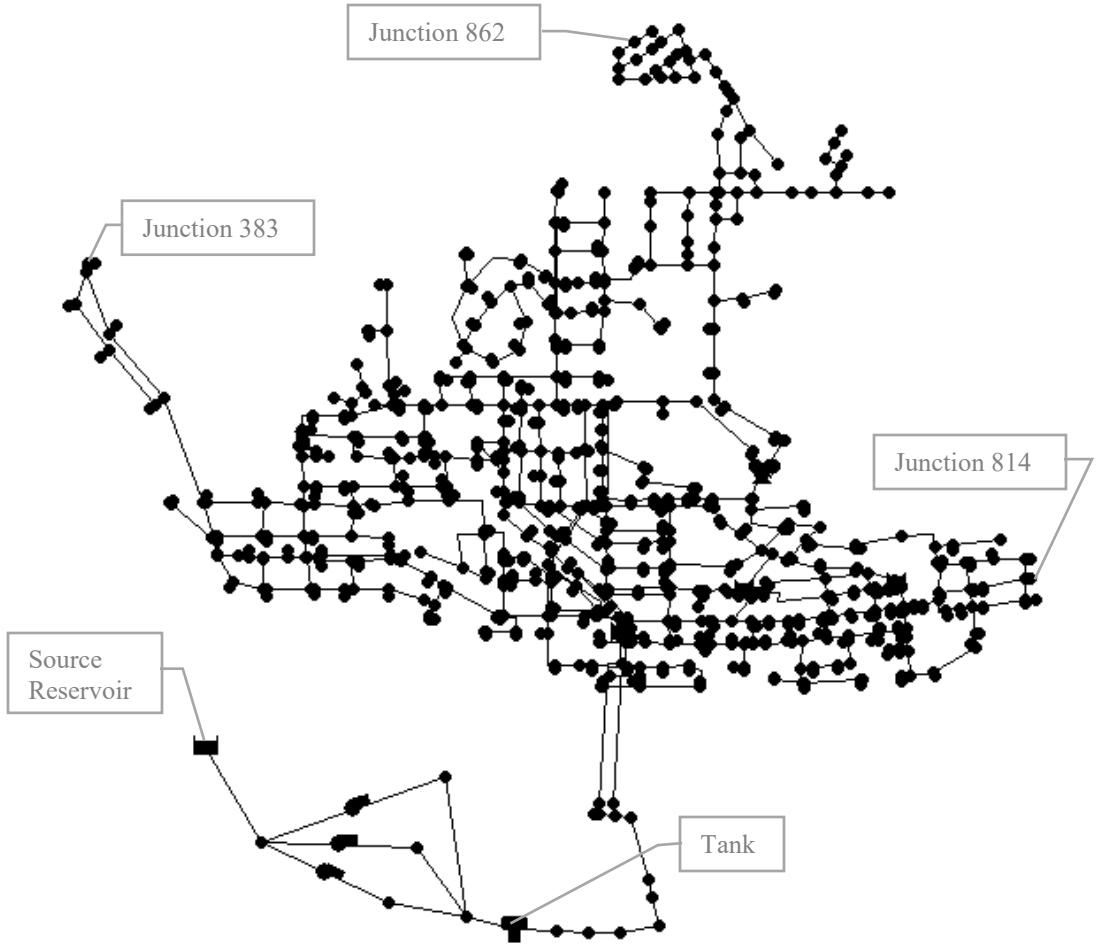

Figure 3.9.a System 9 monitoring junctions.

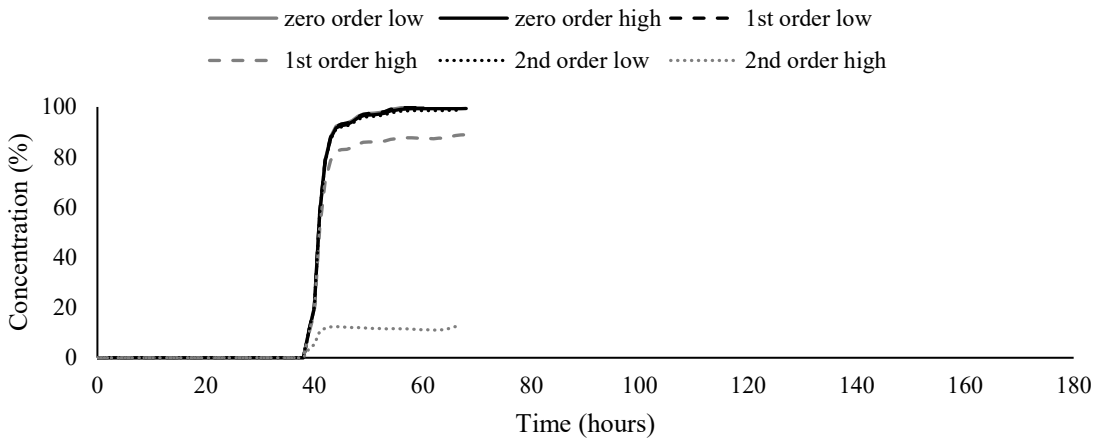

Figure 3.9.b System 9, Junction 383 contaminant spreading history.

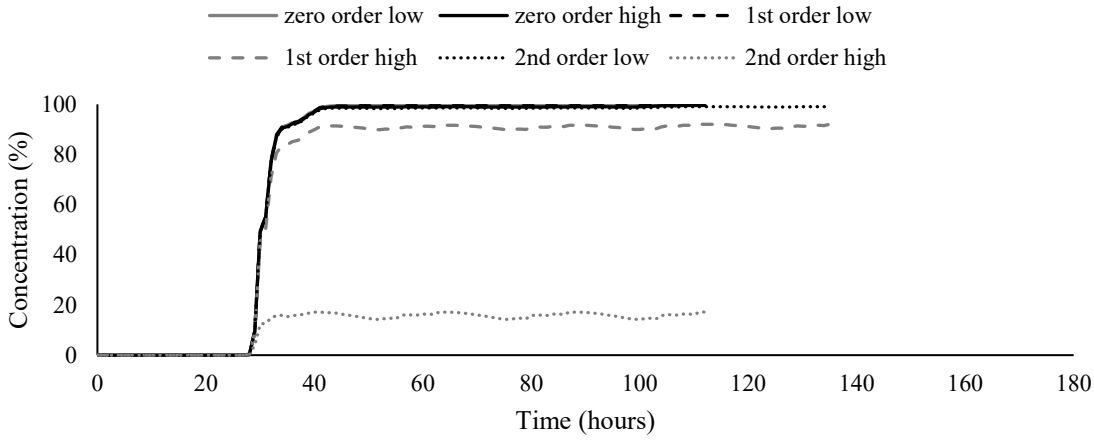

Figure 3.9.c System 9, Junction 814 contaminant spreading history.

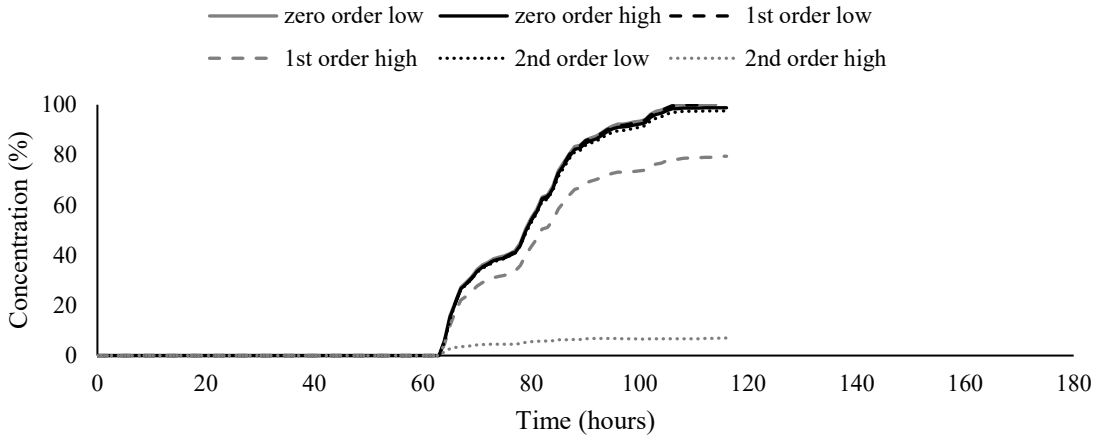

Figure 3.9.d System 9, Junction 862 contaminant spreading history.

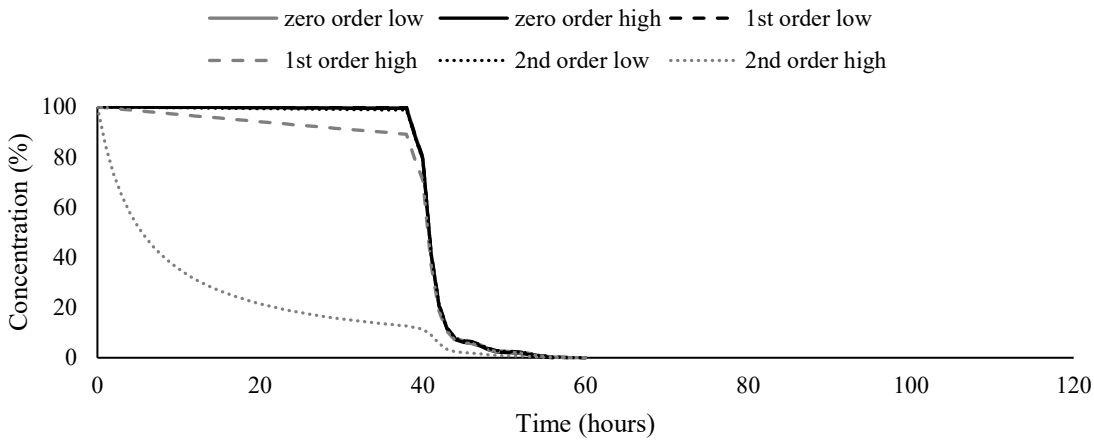

Figure 3.9.e System 9, Junction 383 contaminant clearing history

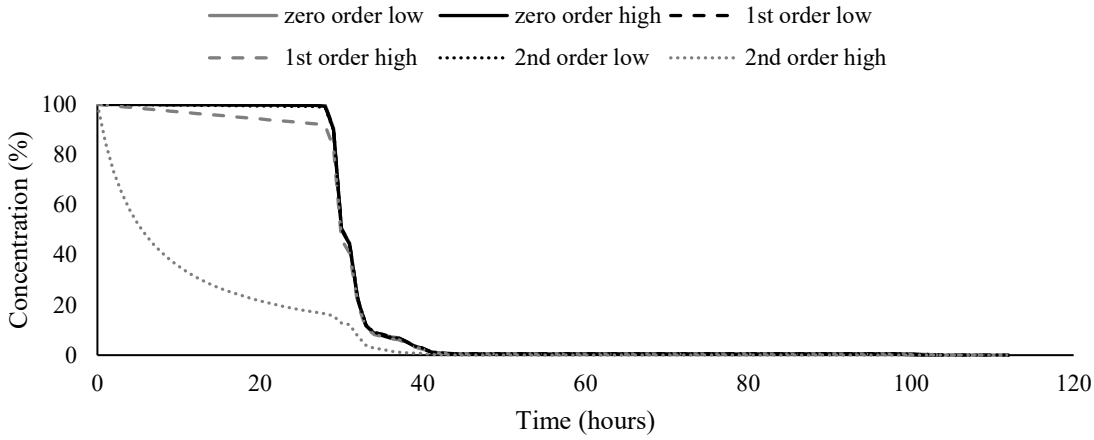

Figure 3.9.f System 9, Junction 814 contaminant clearing history.

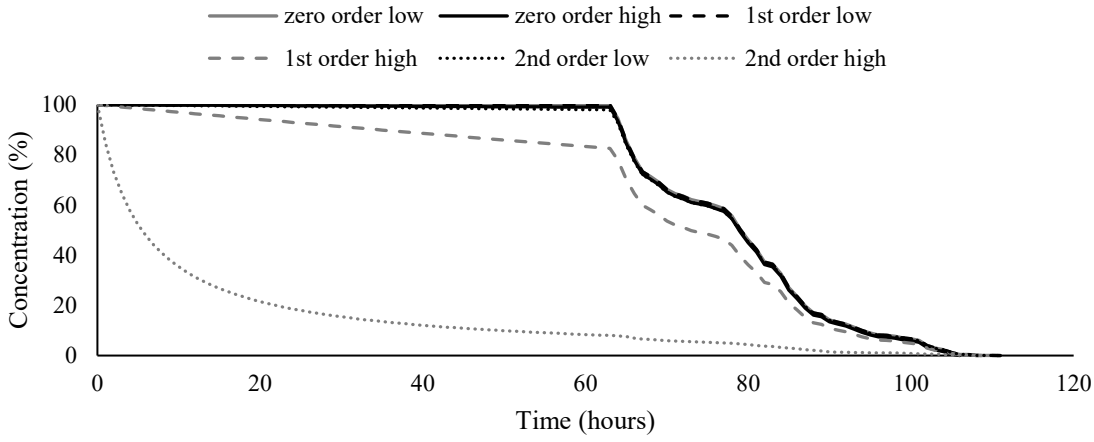

Figure 3.9.g System 9, Junction 862 contaminant clearing history.

System 10, shown in **Figure 3.10.a**, was observed at Junctions 902, 5758, and 12440. Junction 902 was chosen for observation because it had to the longest time to peak concentration, Junction 5758 was chosen as a centrally located point in the system, and Junction 12440 was chosen as a geographically distant point from the sources. Junction 902, shown in **Figure 3.10.b**, had a maximum time to reach peak contamination of 280 hours to reach 84.04% of the source concentration with a zero order K_b of -0.00055 µg/L/day. The minimum time to reach peak contamination was 283 hours to reach a concentration of 57.60% with a first order K_b of -0.07279/day. For Junction 5758, seen in **Figure 3.10.c**, the maximum time to peak contamination was 167 hours to reach 57.53% of the source contamination with a second order K_b of -0.04350 day*µg/L. The minimum time to reach peak contamination was 36 hours to reach a maximum concentration of 100% with a zero order K_b of -0.00055 µg/L/day. Junction 12440, shown in **Figure 3.10.d**, had a maximum time to peak contamination of 167 hours to reach a concentration of 99.05% with a second order K_b of -0.00008 day*µg/L, and a minimum time to reach peak contamination of 156 hours to reach a concentration of 99.99% with a zero order K_b of -0.00055 µg/L/day. For Junction 902, in **Figure 3.10.e**, the maximum time to flush the contaminant from the junction was 202 hours to reach 0% with a zero order K_b of -0.00055 µg/L/day. The minimum time to flush the contaminant from Junction 902 was 166 hours with a zero order K_b of -0.38505 µg/L/day. Junction 5758, seen in **Figure 3.10.f**, had a maximum time to clean all contaminant from the junction of 36 hours for all values of K_b used, except for a zero order K_b of -0.38505 µg/L/day, which took 28 hours to clear from the junction. **In Figure 3.10.g**, the maximum time to clear all contaminant from Junction 12440 was 98 hours with a first order K_b of -0.00027/day, and the minimum time needed to clean the junction was 68 hours for a zero order K_b of -0.38505 µg/L/day.

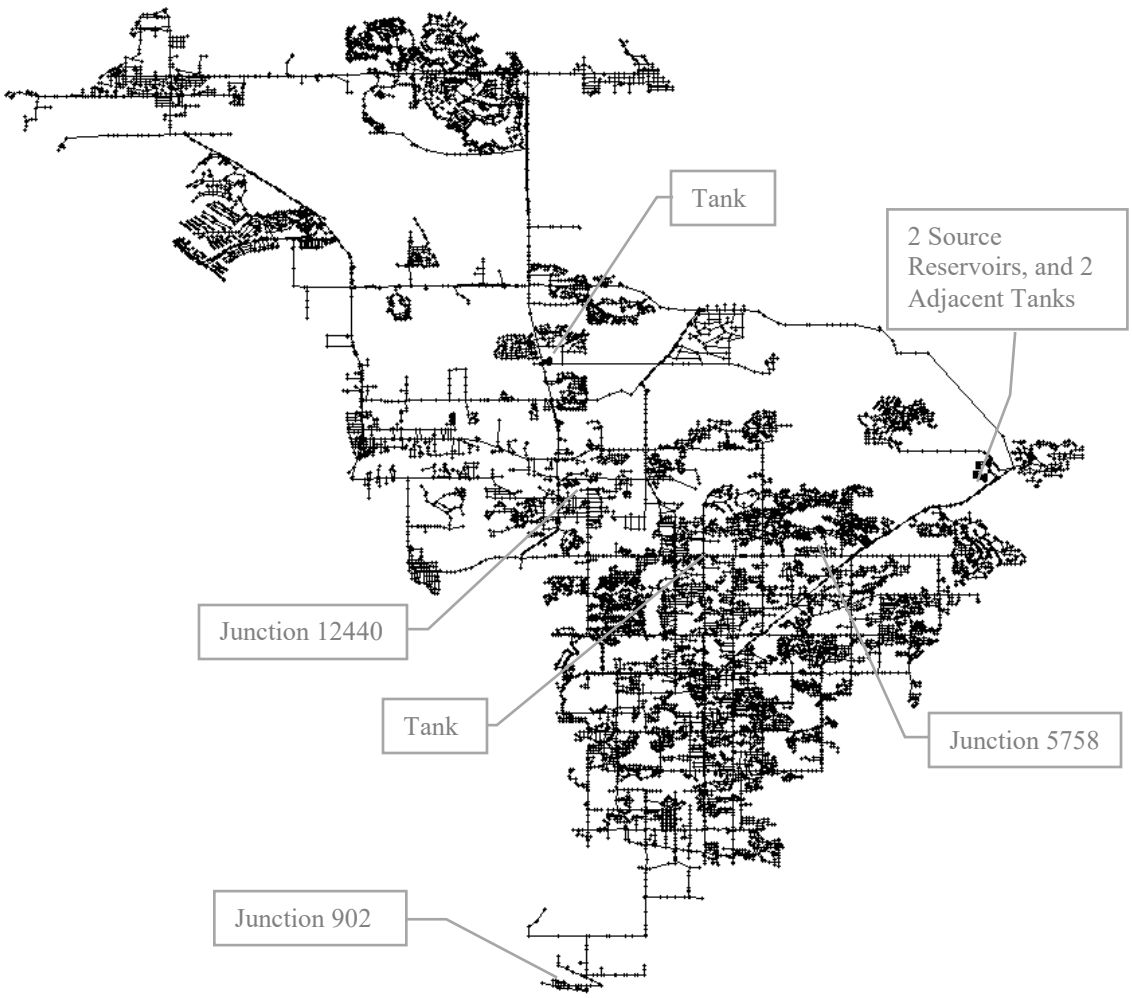

Figure 3.10.a System 10 monitoring junctions.

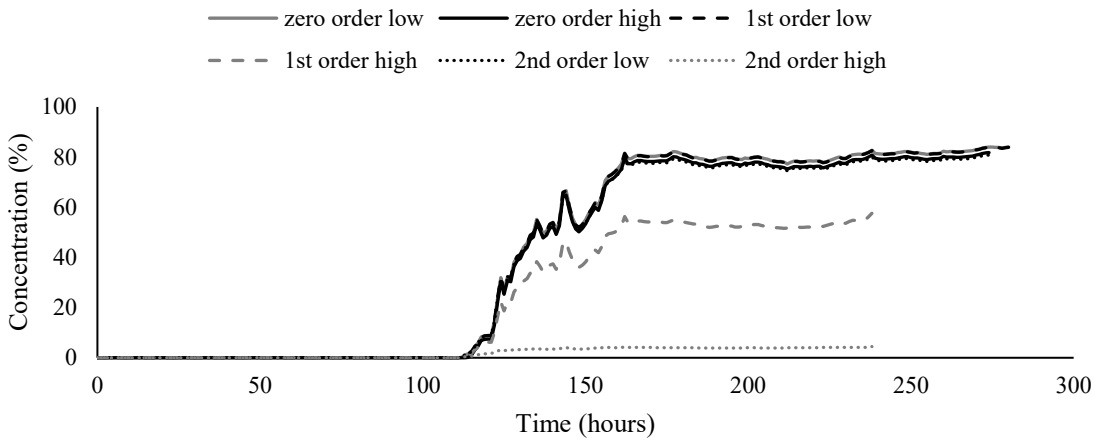

Figure 3.10.b System 10, Junction 902 contaminant spreading history.

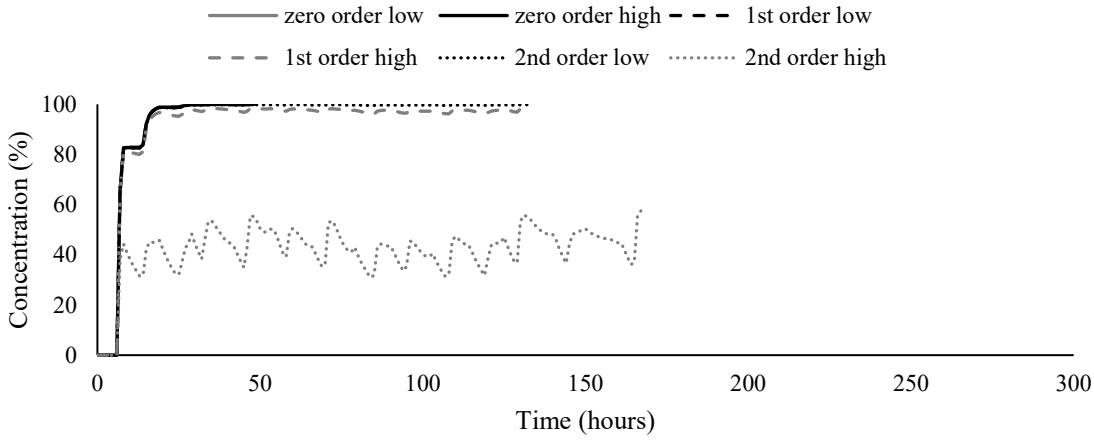

Figure 3.10.c System 10, Junction 5758 contaminant spreading history.

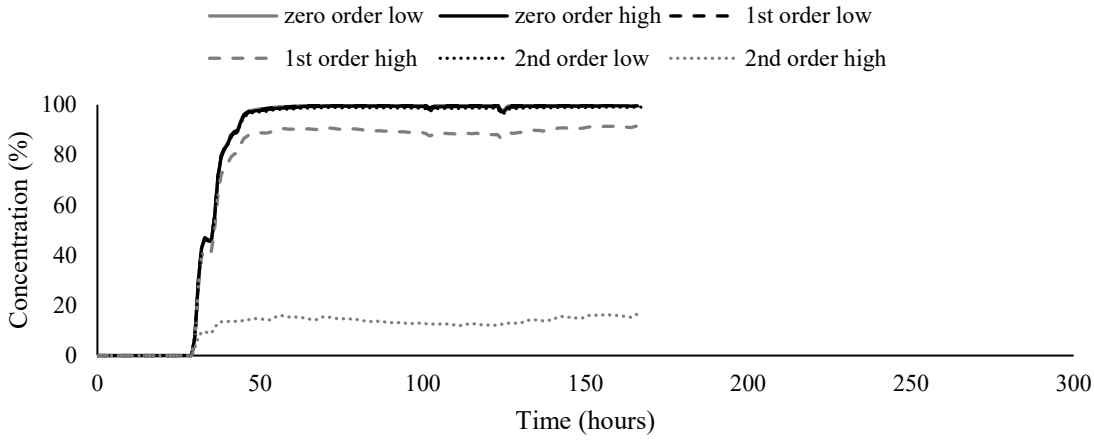

Figure 3.10.d System 10, Junction 12440 contaminant spreading history.

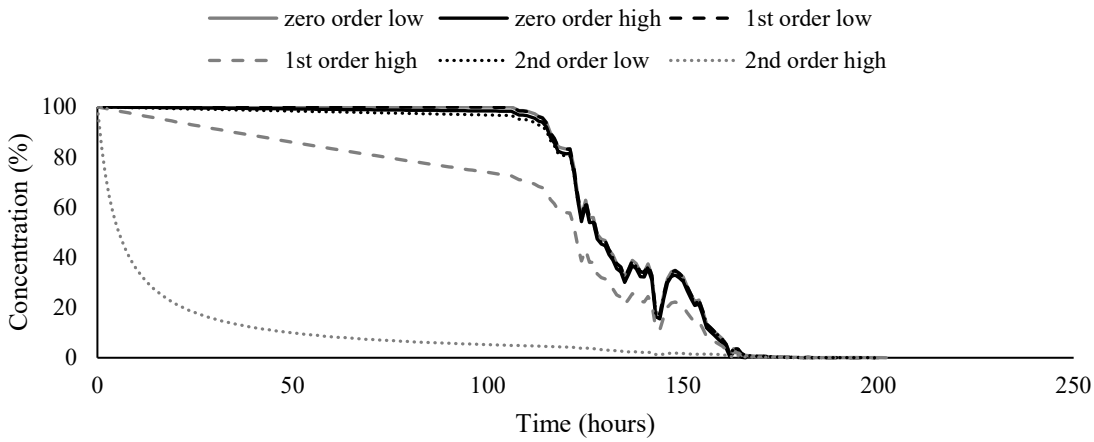

Figure 3.10.e System 10, Junction 902 contaminant clearing history.

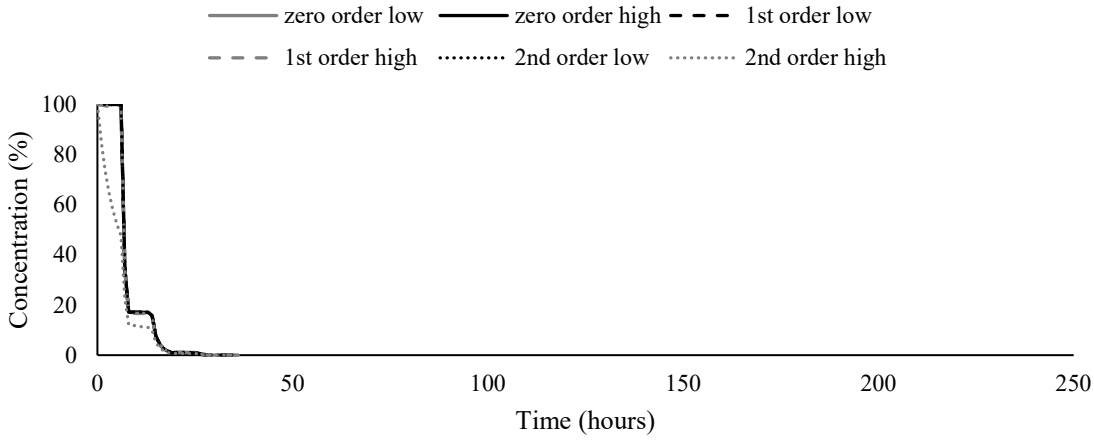

Figure 3.10.f System 10, Junction 5758 contaminant clearing history.

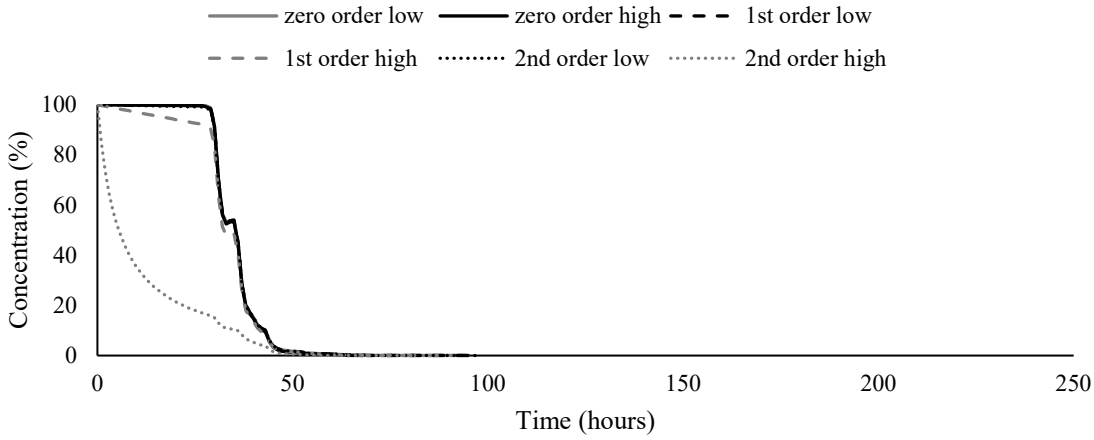

Figure 3.10.g System 10, Junction 12440 contaminant clearing history.

System 11, shown in **Figure 3.11.a**, was observed at Junctions 90, 140, and 170. Junction 90 was chosen as a centrally located point, Junction 140 was chosen as a geographically distant point from the sources, and Junction 170 was chosen as the longest time to reach peak contamination. Junction 90, seen in **Figure 3.11.b**, had a maximum time to reach peak contamination of 44 hours to reach 100% of the source contamination for all values of K_b used, with a maximum concentration of 100% for a zero order K_b of -0.00055 μg/L/day, and first order K_b of -0.00027/day. For junction 140, shown in **Figure 3.11.c**, the maximum time to reach peak contamination was 44 hours for all values of K_b used with a maximum concentration of 100% for a zero order K_b of -0.00055 μg/L/day. Junction 170, in **Figure 3.11.d**, had a time to peak contamination of 60 hours for all values of K_b used, with a maximum concentration of 100% for both a zero order K_b of -0.00055 μg/L/day, and first order K_b of -0.00027/day. The maximum time for Junction 90, shown in **Figure 3.11.e**, to be flushed clean of contaminant was 148 hours for all values of K_b used, except for a second order K_b of -0.04350 day*μg/L, which took 139 hours to clear. For Junction 140, in **Figure 3.11.f**, the maximum time to flush the contaminant from the system was 468 hours for a zero order K_b of -0.00055 μg/L/day, first order K_b of -0.00027/day, and second order K_b of -0.00008 day*μg/L. The minimum time to clear Junction 140 was 257 hours for a second order K_b of -0.04350 day*μg/L. Junction 170, shown in **Figure 3.11.g**, had a maximum time to clear contaminant from the junction of 484 hours for a zero order K_b of -0.00055 μg/L/day, first order K_b's of -0.00027/day and -0.07279/day, and second order K_b of -0.00008 day*μg/L. The minimum time to clear Junction 170 was 129 hours for a second order K_b of -0.04350 day*μg/L.

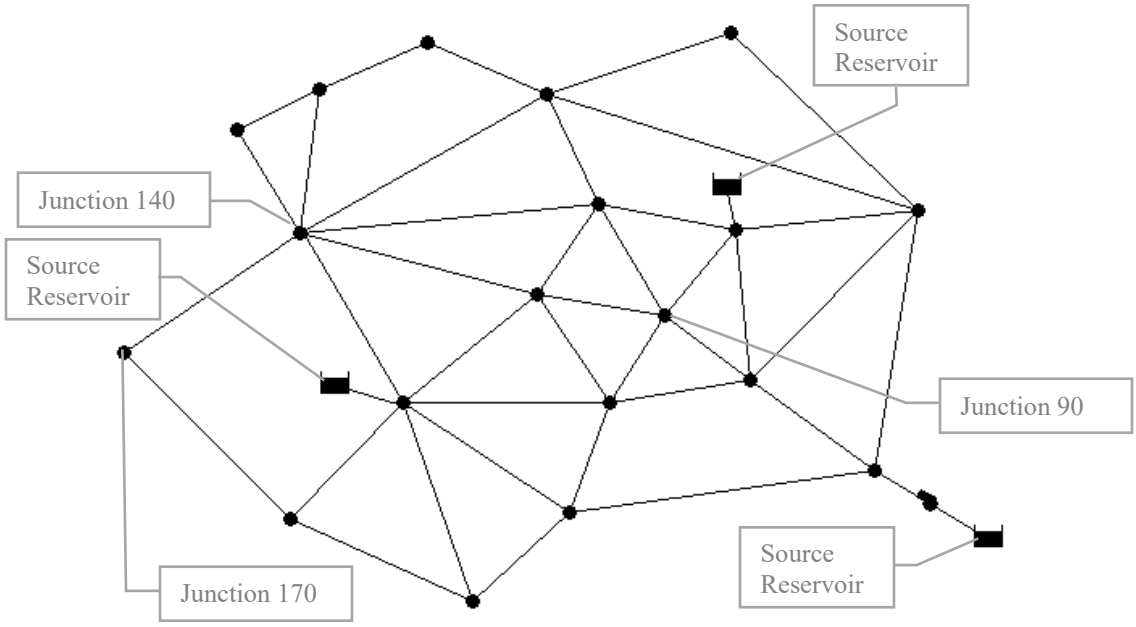

Figure 3.11.a System 11 monitoring junctions.

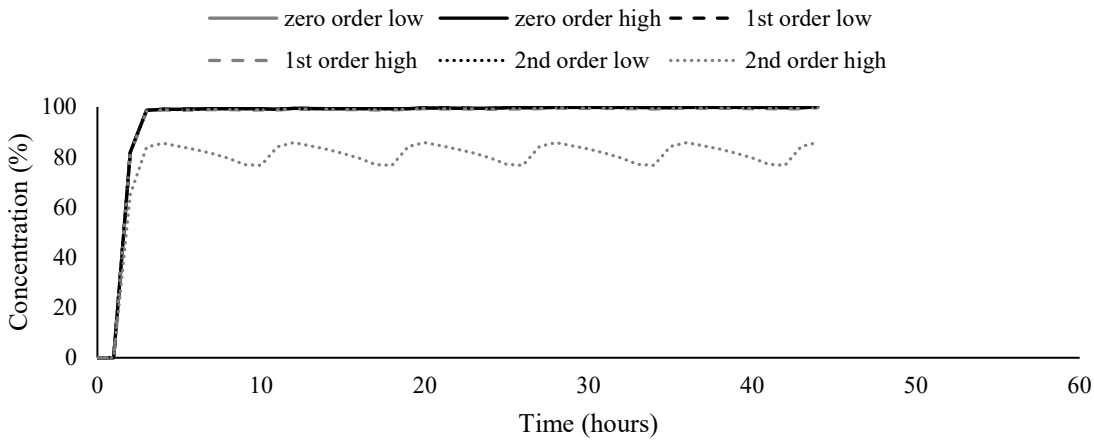

Figure 3.11.b System 11, Junction 90 contaminant spreading history.

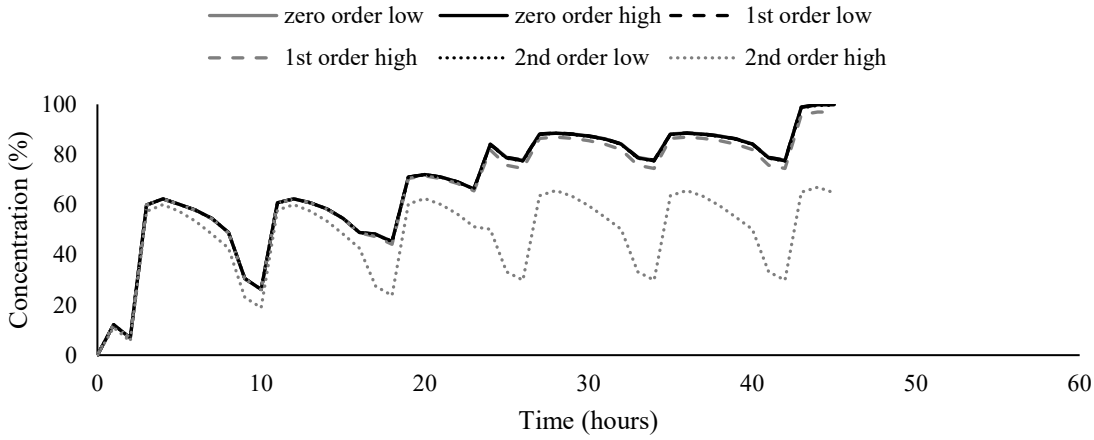

Figure 3.11.c System 11, Junction 140 contaminant spreading history.

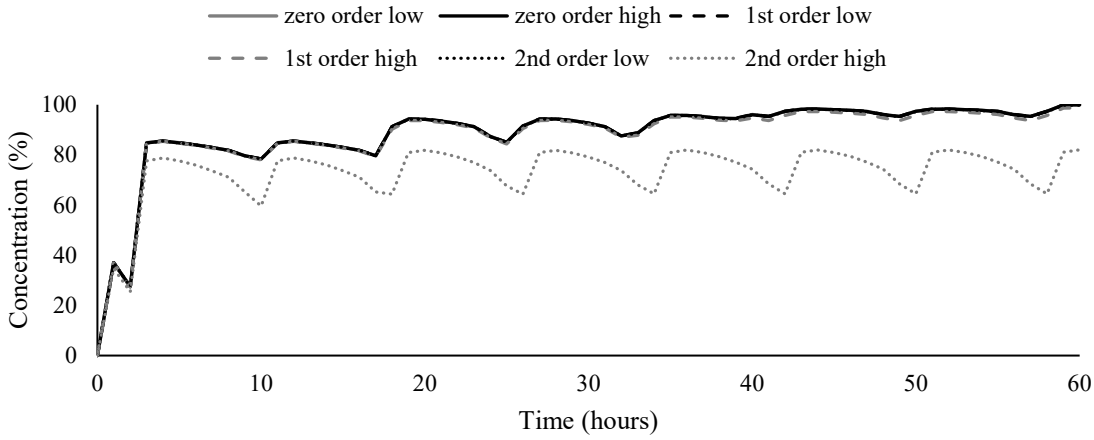

Figure 3.11.d System 11, Junction 170 contaminant spreading history.

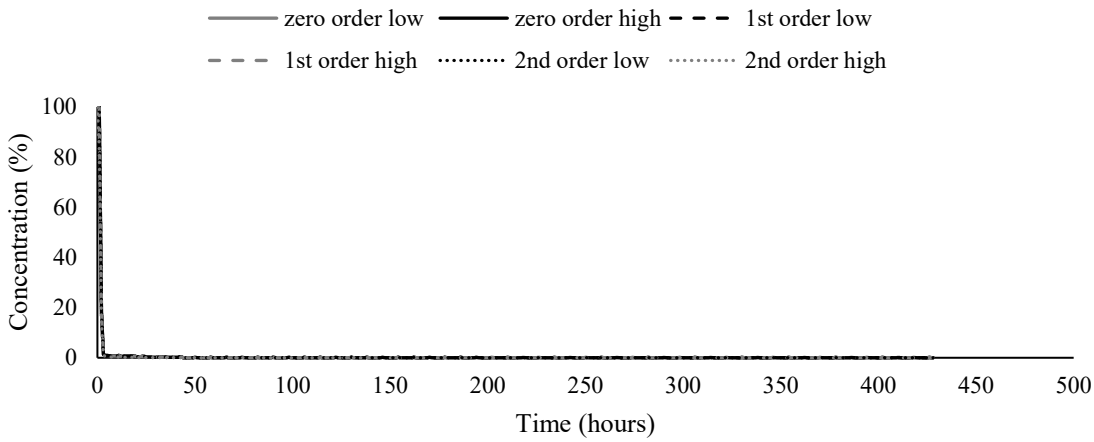

Figure 3.11.e, System 11, Junction 90 contaminant clearing history.

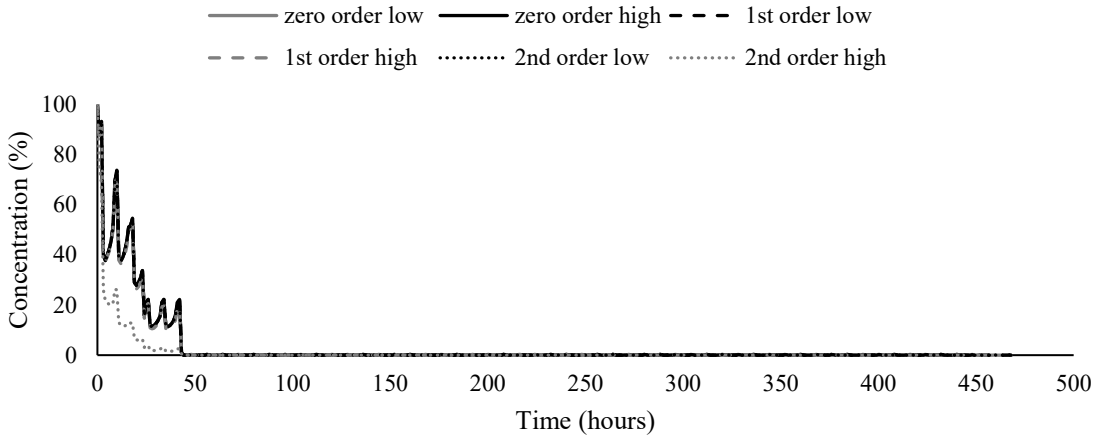

Figure 3.11.f System 11, Junction 140 contaminant clearing history.

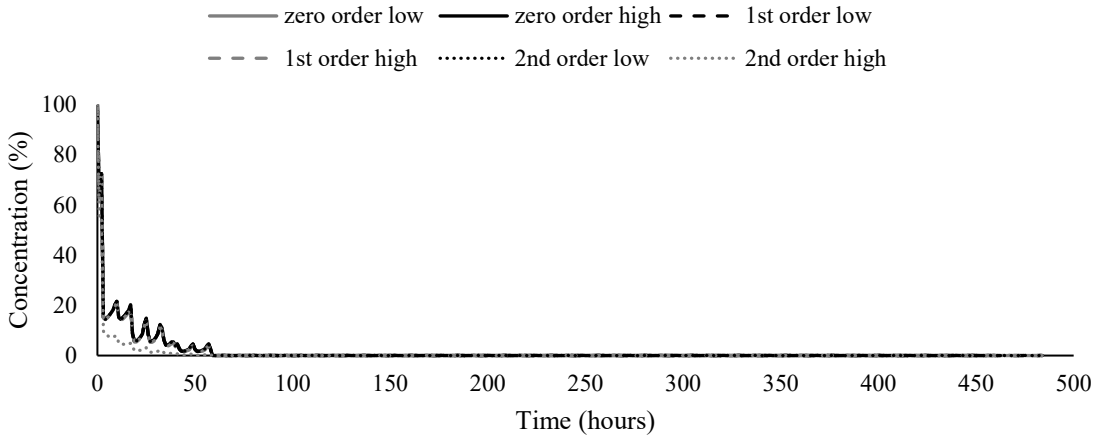

Figure 3.11.g System 11, Junction 170 contaminant clearing history.

System 12, shown in **Figure 3.12.a**, was observed at Junctions 4, 20, and 29. Junction 4 was chosen as the longest time to reach peak contamination, Junction 20 was chosen as a geographically distant point from the source, and Junction 29 was chosen as a centrally located point in the system. Junction 4, shown in **Figure 3.12.b**, had a maximum time to peak contamination of 163 hours to reach a concentration of 98.86% with a second order K_b of -0.00008 day*µg/L, and a minimum time to peak contamination of 19 hours to reach a maximum of 19.39% of the source concentration with a second order K_b of -0.04350 day*µg/L. For Junction 20, in **Figure 3.12.c**, the maximum time to peak contamination was 152 hours to reach a concentration of 99.62% with a zero order K_b of -0.38505 µg/L/day. The minimum time to reach peak contamination was 8 hours to reach a maximum of 31.68% with a second order K_b of -0.04350 day*µg/L. Junction 29, shown in **Figure 3.12.d**, had a maximum time to peak contamination of 139 hours to reach a concentration of 99.98% of the source concentration with a first order K_b of -0.00027/day. The minimum time to peak contamination was 19 hours to reach a maximum of 49.16% with a second order K_b of -0.04350 day*µg/L. Junction 4, in **Figure 3.12.e**, had a maximum time to flush all contaminant from the Junction of 161 hours for both a first order K_b of -0.00027/day, and second order K_b of -0.00008 day*µg/L. The minimum time to clear all contaminant was 90 hours for a zero order K_b of -0.38505 µg/L/day. For Junction 20, shown in **Figure 3.12.f**, the maximum time to clean the contaminant was 151 hours for a zero order K_b of -0.00055 µg/L/day, first order K_b of -0.00027/day, and second order K_b of -0.00008 day*µg/L. The minimum time to flush the contaminant from Junction 20 was 80 hours with a zero order K_b of -0.38505 µg/L/day. For Junction 29, in **Figure 3.12.g**, the maximum time to flush the contaminant is 138 hours for a zero order K_b of -0.00055 µg/L/day, first order K_b of -0.00027/day, and second order K_b of -0.00008 day*µg/L. The minimum time to clear the contaminant is 78 hours for a zero order K_b of -0.38505 µg/L/day.

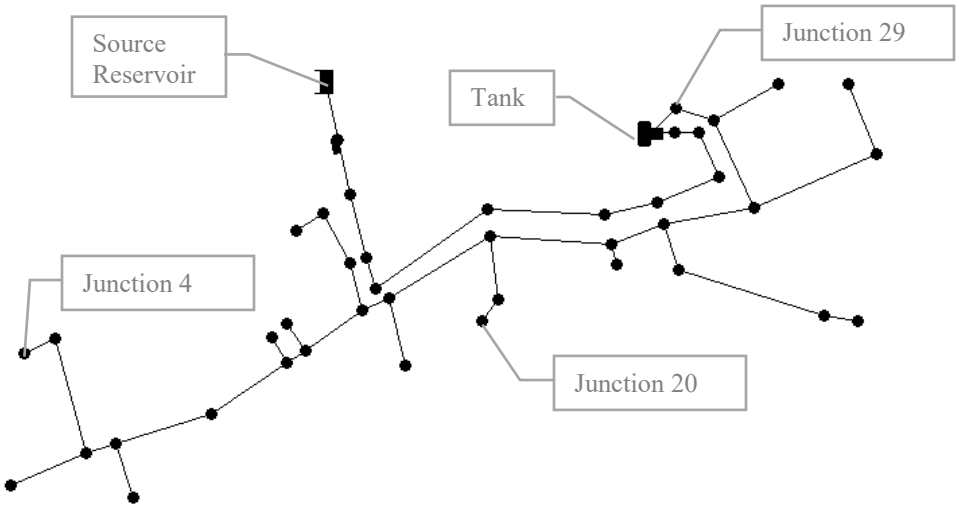

Figure 3.12.a System 12 monitoring junctions.

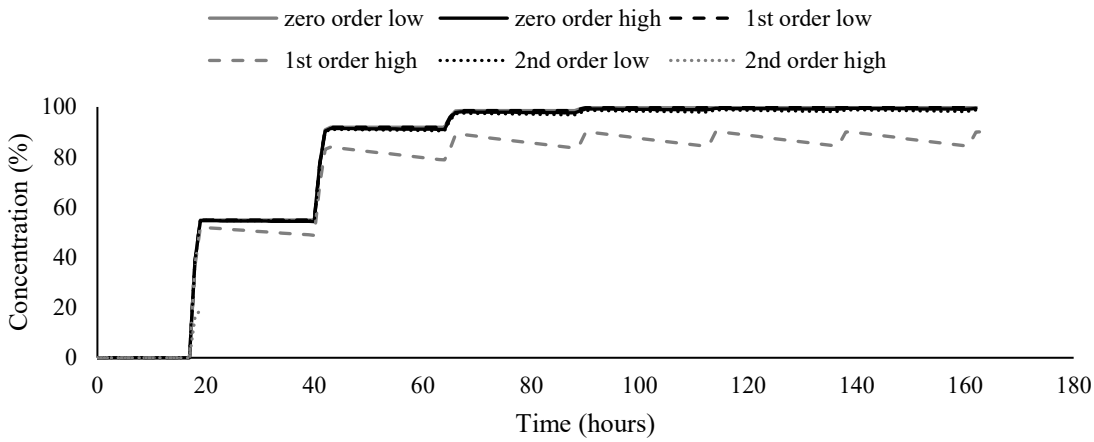

Figure 3.12.b System 12, Junction 4 contaminant spreading history.

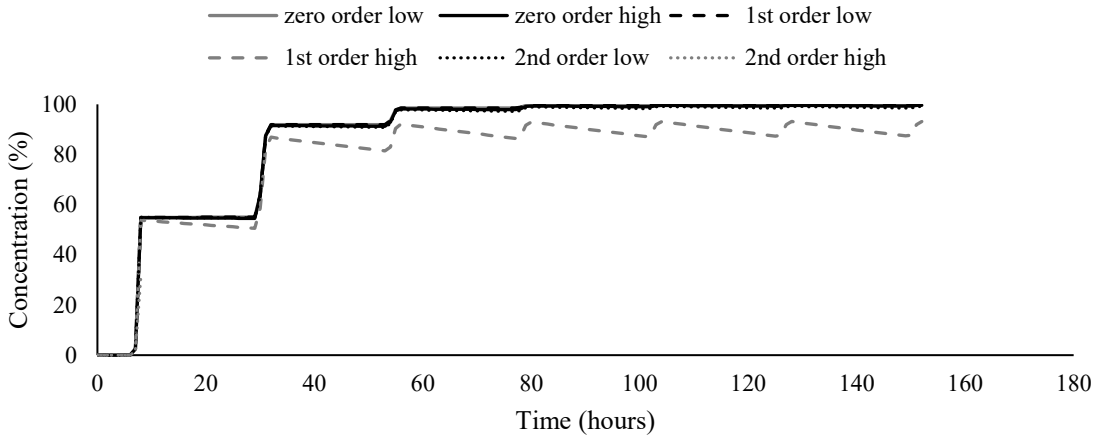

Figure 3.12.c System 12, Junction 20 contaminant spreading history.

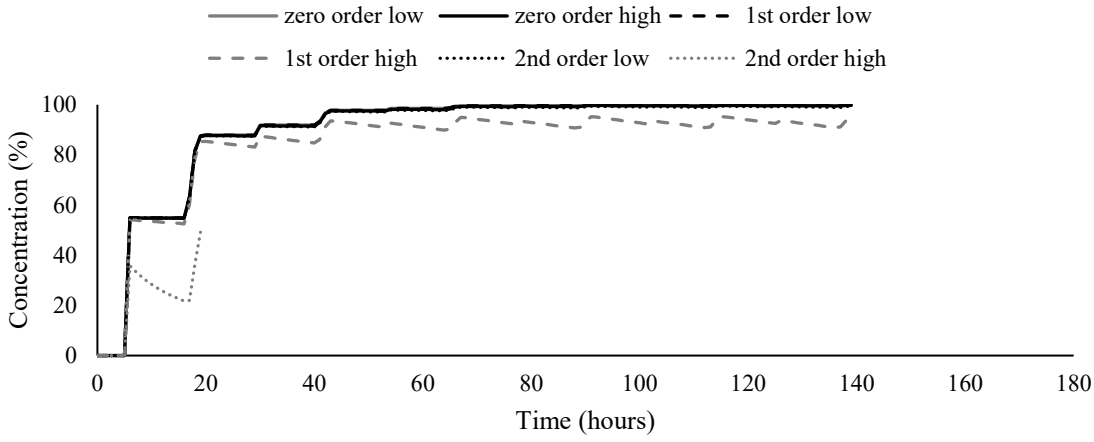

Figure 3.12.d System 12, Junction 29 contaminant spreading history.

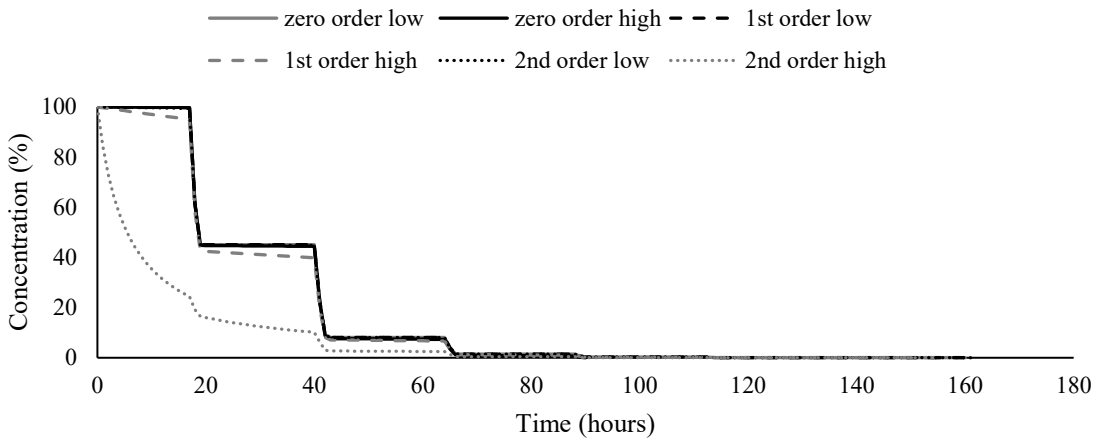

Figure 3.12.e System 12, Junction 4 contaminant clearing history.

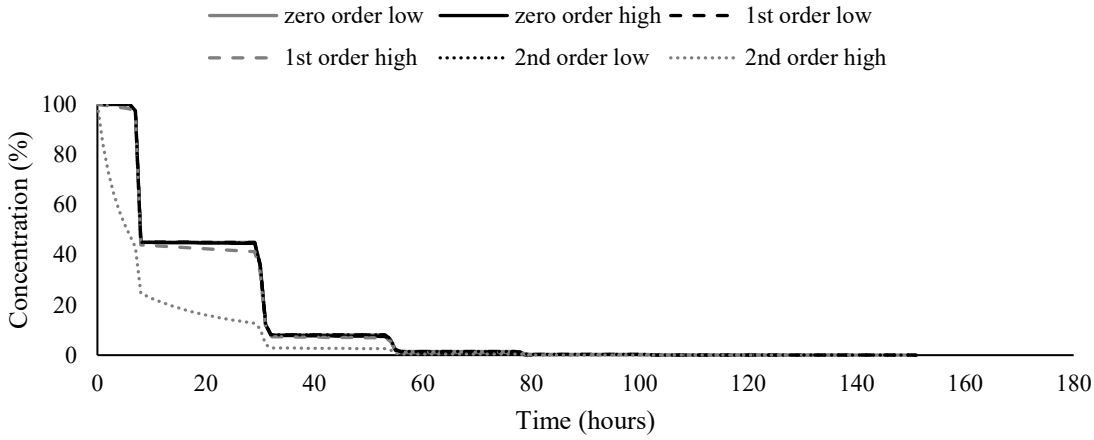

Figure 3.12.f System 12, Junction 20 contaminant clearing history.

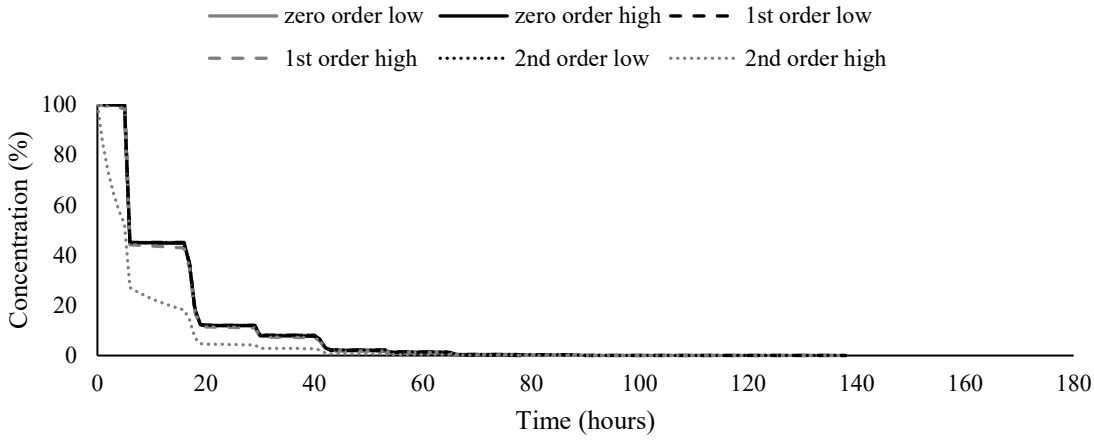

Figure 3.12.g System 12, Junction 29 contaminant clearing history.

System 13, shown in **Figure 3.13.a**, was observed at Junctions 87, 187, and 271. For this system contaminant was only added to surface water reservoirs, and deep groundwater wells were assumed free of emerging contaminants due to the long time period for recharge of deep groundwater wells. Junction 87 was chosen for observation as a centrally located point between contaminated and non-contaminated sources, Junction 187 was chosen as the longest time to reach peak contamination, and Junction 271 was chosen to observe because it is geographically distant from the contaminated sources. Junction 87, shown in **Figure 3.13.b**, had a time to peak contamination of 9 hours for all values of K_b used, reaching a maximum of 100% of the surface water source contamination level with both a zero order K_b of -0.00055 μg/L/day, and first order K_b of -0.00027/day. For Junction 187, in **Figure 3.13.c**, the maximum time to reach peak contamination was 10 hours for all values of K_b used, reaching a maximum concentration of 36.43% for both a zero order K_b of -0.00055 μg/L/day, and first order K_b of -0.00027/day. Junction 271, shown in **Figure 3.13.d**, had a maximum time to peak contamination of 9 hours to reach a concentration of 99.97% with a zero order K_b of -0.38505 μg/L/day, and a minimum time to peak contamination of 8 hours to reach 100% for both a zero order K_b of -0.00055 μg/L/day, and first order K_b of -0.00027/day. The maximum time to clear all contamination from Junction 87, shown in **Figure 3.13.e**, was 9 hours for a zero order K_b of -0.00055 μg/L/day, first order K_b's of -0.00027/day and -0.07279/day, and second order K_b of -0.00008 day*μg/L. The minimum time to flush all contaminant from the junction was 7 hours for a zero order K_b of -0.38505 μg/L/day, and second order K_b or -0.04350 day*μg/L. For Junction 187, in **Figure 3.13.f**, the maximum time to flush all contaminant was 9 hours for all values of K_b used. Junction 271, in Figure **3.13.g**, had a maximum time to clear all contaminant from the junction of 8 hours for all values of K_b used.

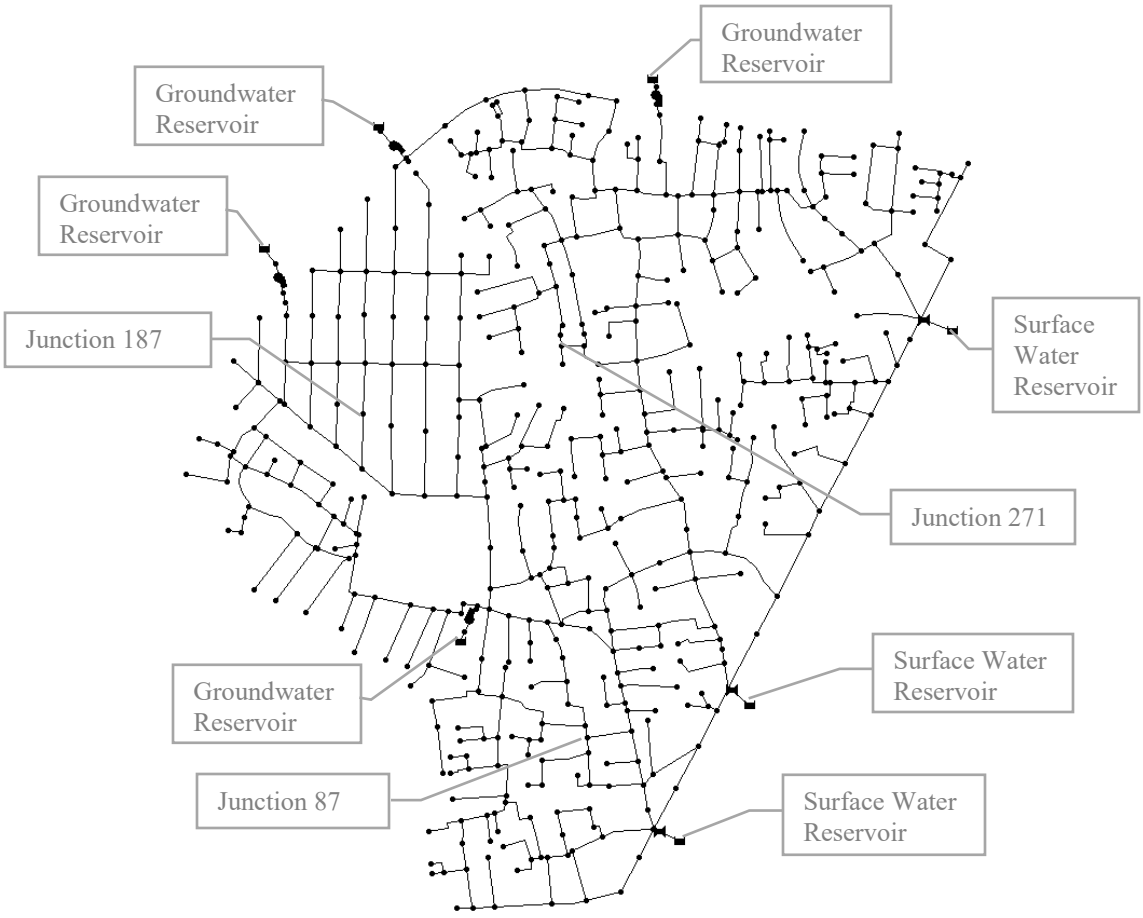

Figure 3.13.a System 13 monitoring junctions.

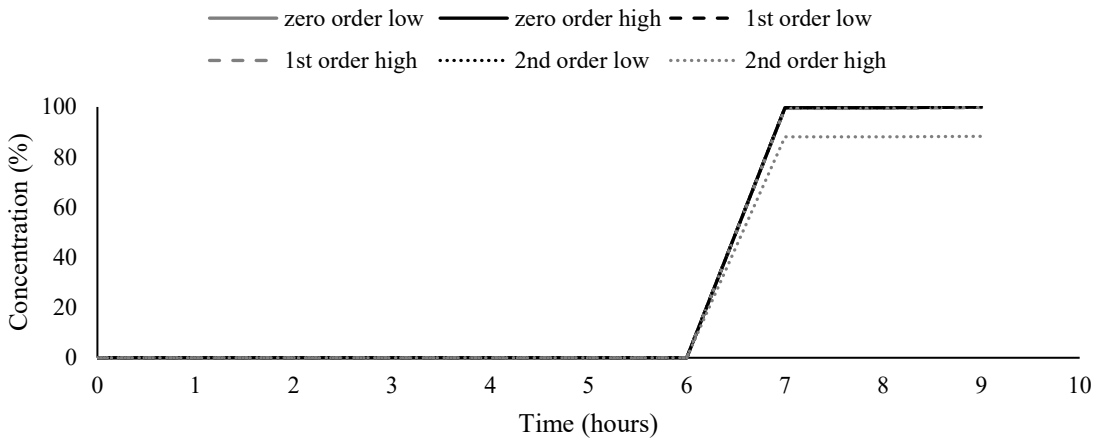

Figure 3.13.b System 13, Junction 87 contaminant spreading history.

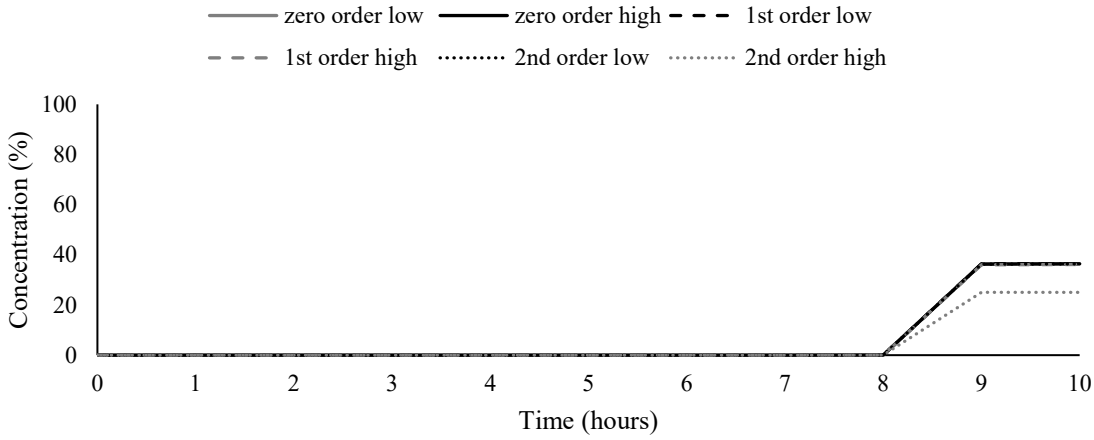

Figure 3.13.c System 13, Junction 187 contaminant spreading history.

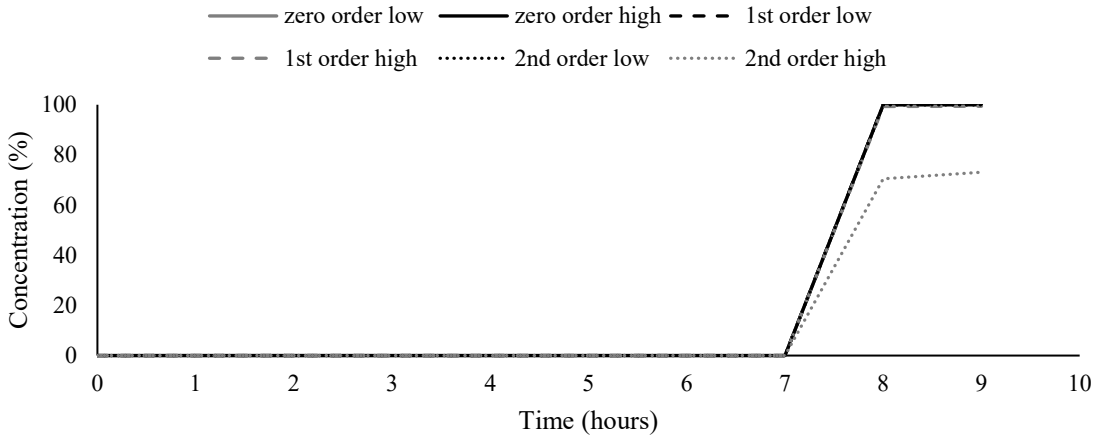

Figure 3.13.d System 13, Junction 271 contaminant spreading history.

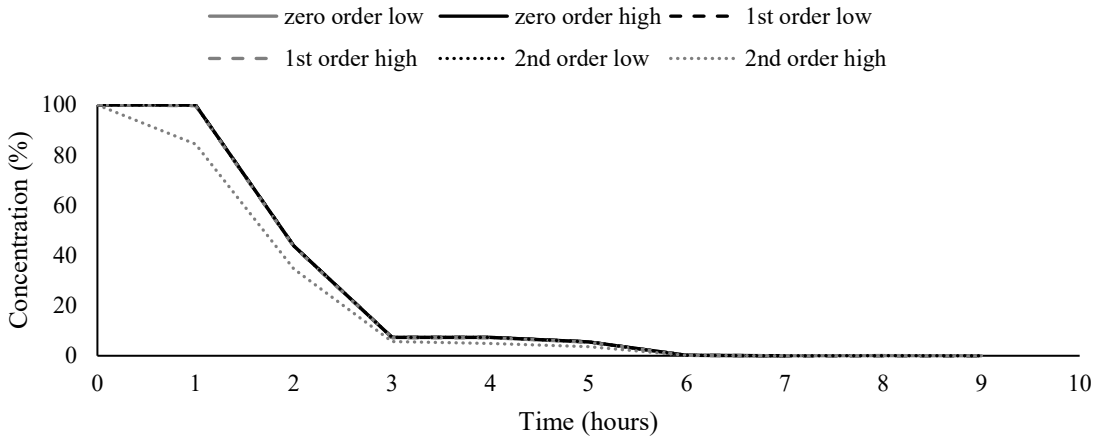

Figure 3.13.e System 13, Junction 87 contaminant clearing history.

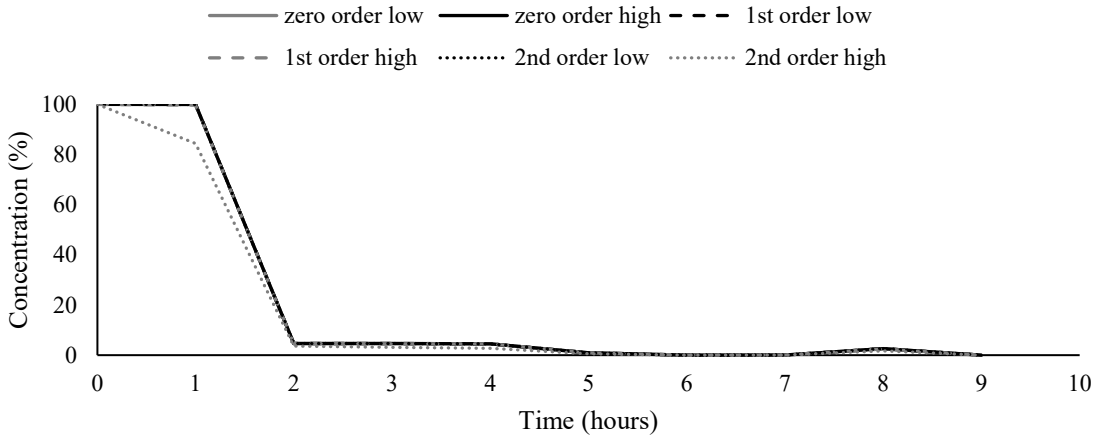

Figure 3.13.f System 13, Junction 187 contaminant clearing history.

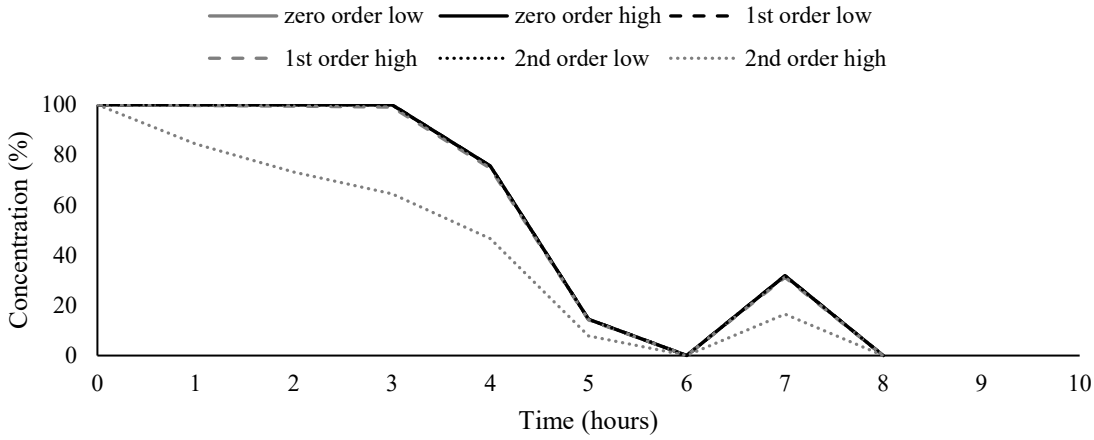

Figure 3.13.g System 13, Junction 271 contaminant clearing history.

A summary of "worst-case scenarios" for each system are shown in **Table 3.1**. The minimum time to reach peak contamination among the observed junctions for each system represents the worst-case scenario of how quickly a junction will become contaminated once the source water has been contaminated. The maximum time to clear the contaminant represents the worst-case scenario of how long it could potentially take to clear a system of contaminant under normal use after the source water has been cleaned of contaminants. Comparing the systems total pipe volume shows that there is no clear trend between system volume and time to contaminate or clear.

Table 3.1 Worst-case times for contaminant spreading and clearing for each system

System Number	Pipe Volume (ft^3)	Minimum Time to Contaminate (hr)	Maximum Time to Clear (hr)
1	43	8	279
2	1,108	41	248
3	522	37	45
4	18,544	7	171
5	7,830	7	348
6	128,095	29	1,591
7	31,026	12	276
8	29,411	63	994
9	111,453	60	112
10	3,573,383	36	202
11	83,383	44	484
12	87,915	8	161
13	16,317	8	9

System 6 (**Figure 3.6.a**) was chosen to observe across a wide range of first order K_b values because of its short time to reach maximum contamination levels and long time to clear of contaminant. The time to exceed a reasonably high percentage (90%) of the source contamination level across the complete range of K_b values from -0.00001/day to -0.5/day, selected to give a slightly wider range than those calculated using experimental data from Gibs et al. (2007) are shown in **Figure 3.14.a** for Junctions 11, 57, and 102. **Figure 3.14.b**

shows the time to clear all contaminant from Junctions 11, 57, and 102 across the same range of K_b values.

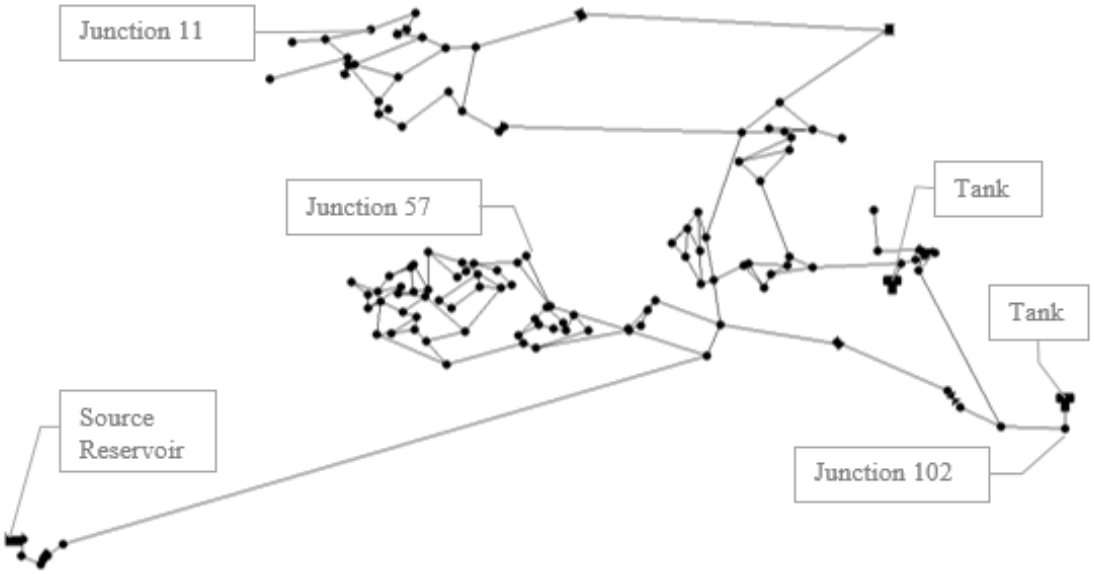

Figure 3.6.a System 6 monitoring junctions (repeated for convenience).

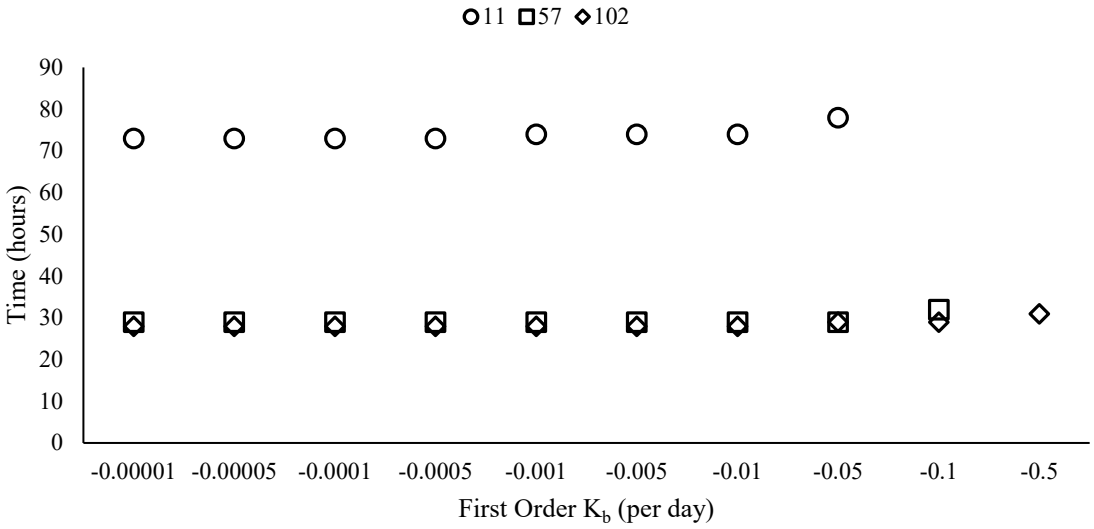

Figure 3.14.a Time to exceed 90% contaminant in System 6.

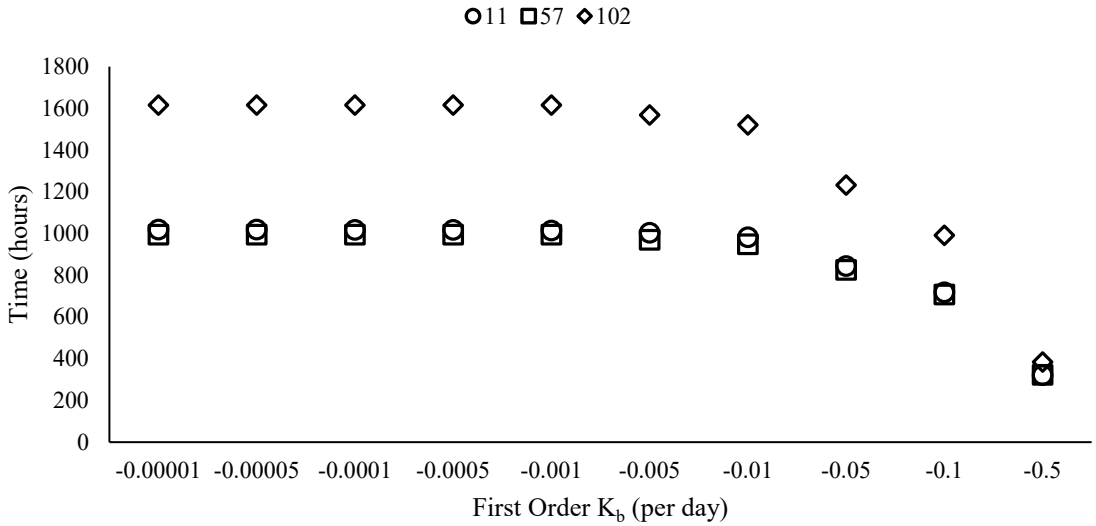

Figure 3.14.b Time to clear all contaminant in System 6.

The maximum time to contaminate for each system was normalized to t/t_{max} as shown in **Figure 3.15.a**. The systems, described in **Table 3.2**, were then compared by layout type and storage tank location. In **Figure 3.15.b**, the systems with branched layouts were compared. Systems with looped layouts are shown in **Figure 3.15.c**. Systems in which the tank was located near the source can be seen in **Figure 3.15.d**, and with tanks far from the source in **Figure 3.15.e**. Systems without a storage tank are shown in **Figure 3.15.f**.

Table 3.2 System Descriptions

System	Pipe Volume (ft^3)	Type	Tank Location
1	43	branched	Near Source
2	1,108	branched	Near Source
3	522	branched	Near Source
4	18,544	looped	Far From Source
5	7,830	looped	Far From Source
6	128,095	looped	Far From Source
7	31,026	looped	Far From Source
8	29,411	looped	Far From Source
9	111,453	looped	Near Source
10	3,573,383	looped	2 Near and 2 Far From Source
11	83,383	looped	No Tank
12	87,915	branched	Far From Source
13	16,317	looped	No Tank

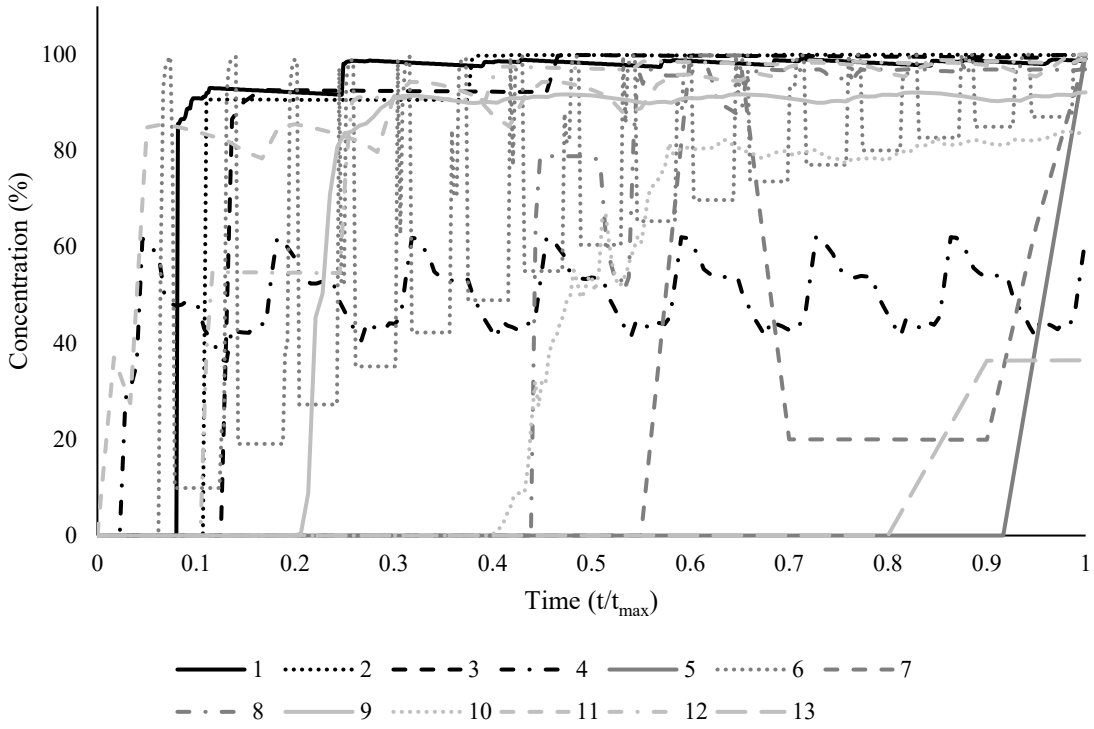

Figure 13.15.a Maximum time to contaminate for each system.

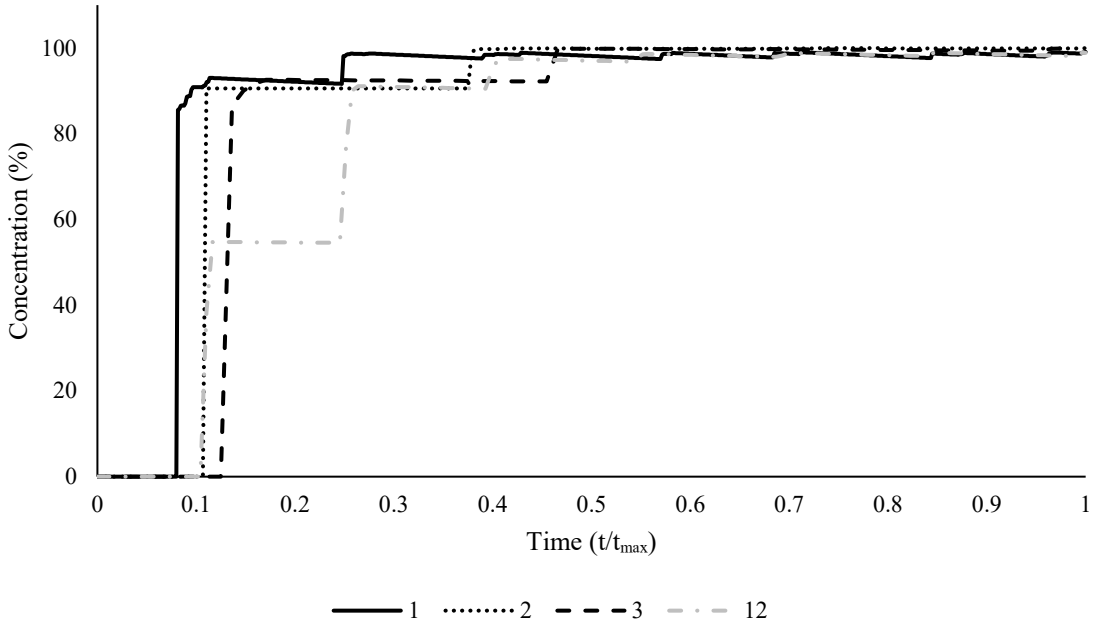

Figure 3.15.b Time normalized contamination history for branched systems.

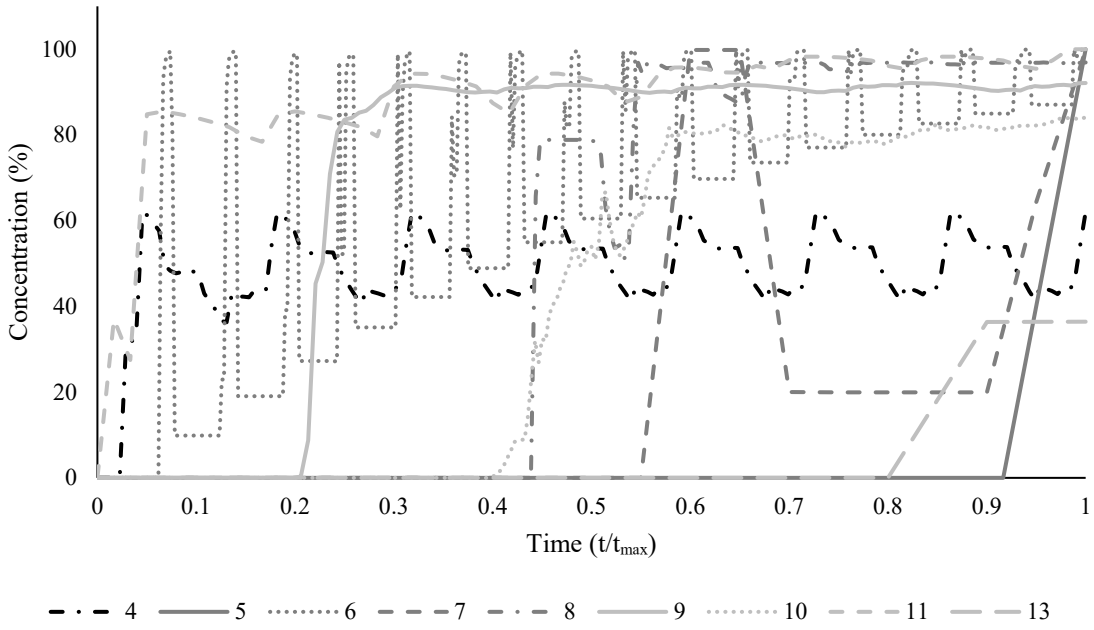

Figure 3.15.c Time normalized contamination history for looped systems.

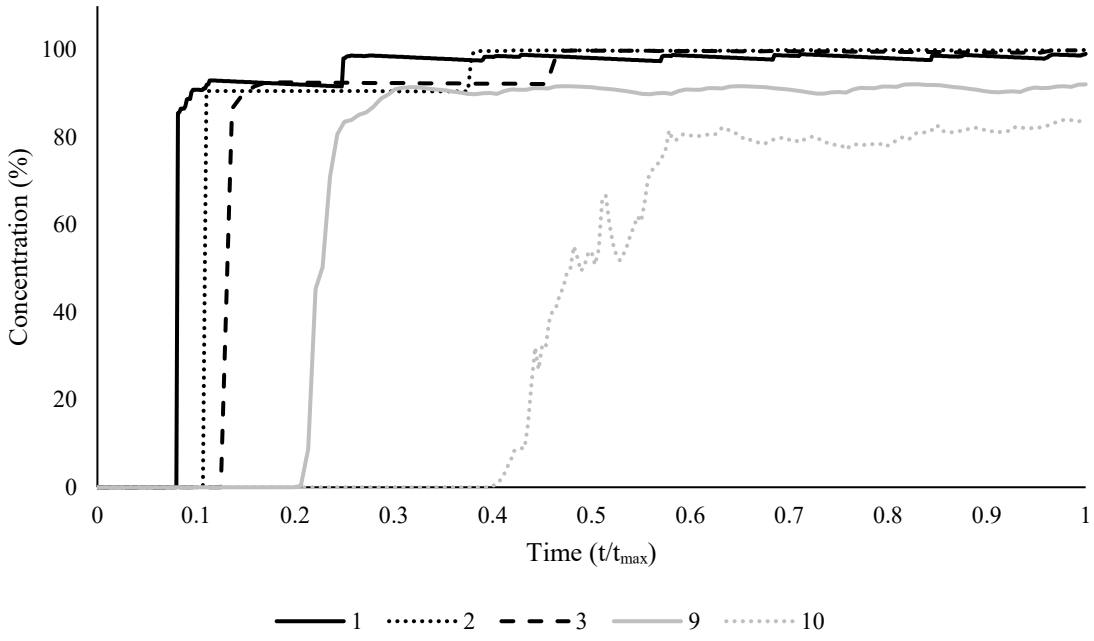

Figure 3.15.d Time normalized contamination history for systems with tank near the source.

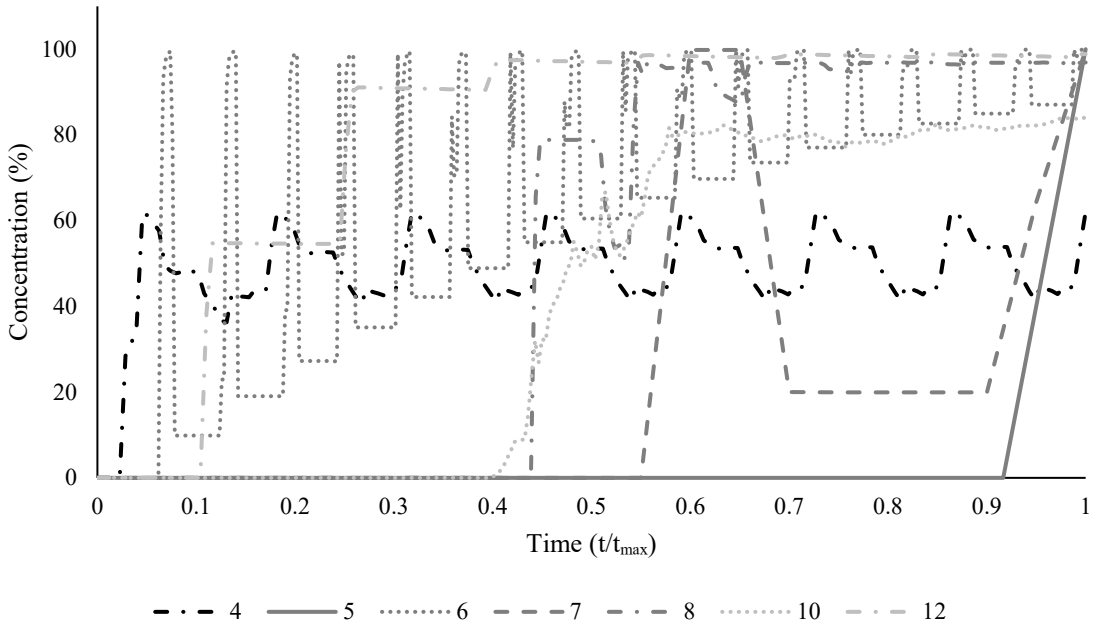

Figure 3.15.e Time normalized contamination history for systems with tank far from the source.

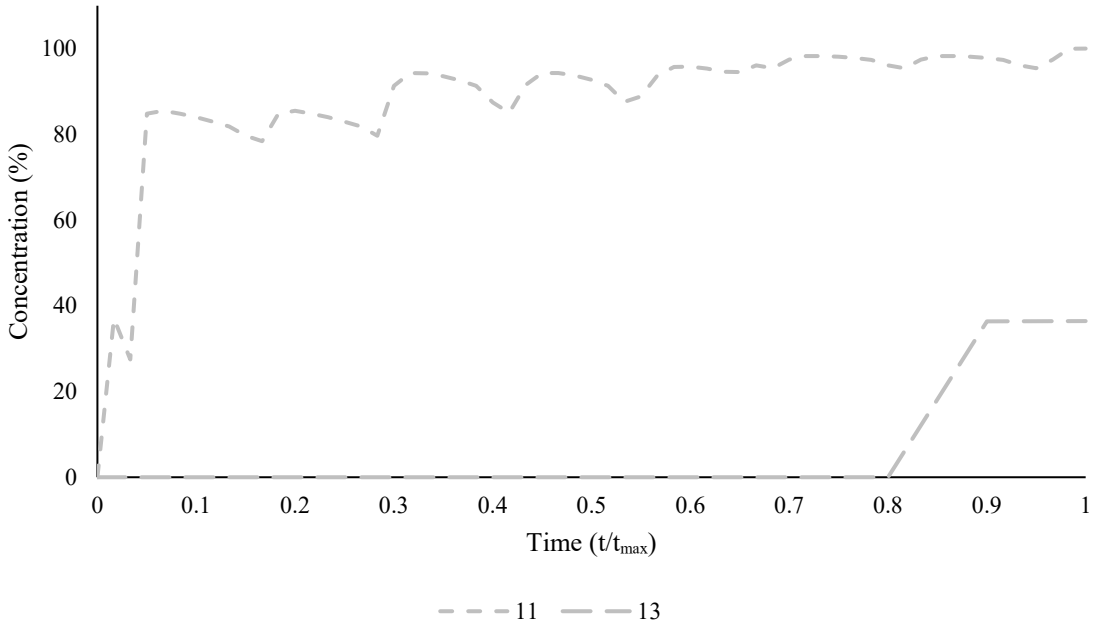

Figure 3.15.f Time normalized contamination history for systems without tanks.

4 Conclusions

Based on the results of this study, emerging contaminants with a relatively high rate of second order decay should be considered of least concern due to decaying faster than can be built up in the system by a continuous release into source waters. Having a relatively high or low rate of zero or first order decay, or low second order decay made negligible difference in the concentration of contaminants building up in the systems. This confirms the hypothesis that higher decay coefficient and higher order of decay would result in less buildup in the system, however it was also expected that a difference would have been seen within the same order between the high and low value of K_b for zero and first order which was not observed in the results of this study. It was expected that the furthest junction from the source would have the longest time to reach peak contamination, but this was not found to always be true. There was no clear connection between the observed factors and the systems in which the furthest junction was not the longest. This may be due to differences in demand in and near the observed junctions, however demand was not considered in this study. System volume was predicted to have a proportional effect on the time to become contaminated and to clear of contamination, however this was not seen in the results.

It was found that branched systems without loops were cleared of contaminants more quickly relative to the time for that system to become fully contaminated than systems containing loops. This was against the initial hypothesis that looped systems would clear more quickly due to having more opportunity to circulate clean water to the junctions, and may have been due to the branches pushing the contaminated water straight out through the junctions without circulating it back around in a loop. Systems with no tank cleared quickly while systems containing tanks took longer to clear of contamination due to the longer storage time of water inside the tanks as was predicted in the hypothesis.

Concentration of contaminants fluctuated with filling and emptying of storage tanks and with daily fluctuations of demand at the junctions as was expected based on the results of Clark et al. (1993) and tank position was found to have an observable effect on the amount of fluctuation. Systems in which the tank was located near the source reservoir experienced less fluctuation in concentration than systems with tanks located far from the source. Systems with no storage tank experienced the least amount of fluctuation in contaminant concentration because they were only influenced by the fluctuating demand in the system. In addition, a smaller 24-hour fluctuation was seen corresponding to diurnal user demands.

Sufficiently high K_b values result in systems never reaching above 90% source contamination level but did not significantly affect the time required to reach peak contamination. For System 6 (**Figure 3.14.a**) the cutoff value for K_b was -0.1/day after which the concentration of contaminant began to not exceed the 90% target. This was against the prediction that the time to become contaminated would be sensitive to changes in decay coefficient. Based on this result if a system is found to become contaminated to a potentially risky concentration of an emerging contaminant, the time for the system to be fully contaminated above 90% of the concentration in the source reservoir will not differ across a wide range of decay rates reducing the need for several simulations to be run to

determine the time until the entire system may be in danger if the rate of decay of the CoC is not known. For system clearing, time to reach 0% concentration was insensitive to K_b until a K_b value of -0.01/day, after which the time value decreased linearly for all studied junctions. This partially confirmed the hypothesis that time to clear a system of contaminant would be sensitive to decay coefficient. If a contaminated system were being cleared, the time needed to clear would not change with decay rate of the CoC unless it had a relatively high decay coefficient.

When the maximum time to become contaminated was normalized for each system it was shown that branched systems followed a similar pattern, while looped systems were harder to predict. Systems with a tank located near the source followed a similar pattern, and less fluctuation in concentration was observed compared to those with the storage tank located far from the source. There was no clear effect of having no tanks. There are many factors contributing to each individual systems behavior so it may not be possible to generalize across system types. Based on the results of this study an ideal water distribution system for clearing contaminants quickly would be branched and contain no storage tanks, however this design comes with trade-offs to practical use in developed. Loops provide a system with more reliability as they create alternate routes to supply water users in the system should a pipe be shut off, and storage tanks provide additional water to help cover peak usage times such as hydrants pulling large amounts of additional water during a fire emergency, as well as helping to provide additional water pressure within the system (Gilbert, 2012).

The results of this study are generalized, but may help provide future studies with a baseline to help determine what levels of exposure a person may experience based on the type and size of a water distribution system and the decay rates of the contaminant. Additional study will be needed to determine the decay rates of individual emerging contaminants, the levels at which they effect humans and the environment, and how these contaminants can be removed more effectively during the water treatment process.

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