A Graphical Procedure for Sensor Placement Guidance for Small Utilities

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Abstract

Efforts to improve water security have led to the development of Contamination Warning Systems (CWS) aimed at providing early indication of contamination, accidental or intentional, in drinking water systems. Sensors that detect changes in water quality are a critical component. Because the extent of any monitoring system is constrained by a limited budget, focus is placed on optimizing the placement of sensors to maximize their ability to detect contamination and protect human health. Robust models and algorithms have been developed to recommend sensor deployment, but many require hydraulic/water quality models. Small utilities typically do not possess the resources to develop models, so this study developed a simple graphical procedure to recommend placement of one water quality sensor without a model or complicated algorithm. This method allows utility managers to utilize basic information about the geometry of their network to determine near optimal sensor placement in limited time without complicated software.

INTRODUCTION

Protection of water systems from possible terrorist attacks has become a priority of both federal and local agencies in recent years. Research efforts aimed at improving water security and minimizing threats to drinking water systems have led to the development of Contamination Warning Systems (CWS). The goal of a CWS is to provide early indication of a contamination event in a distribution system with the intent to reduce public health and economic impacts. Even if the probability of intentional contamination by introduction of chemical, radioactive, or micro-biological contaminants is low, the related damaging effects are high (Cozzolino et al., 2011).

Although the recent focus on CWS development has emerged from the increased concern of intentional contamination from terrorist attacks, accidental contamination of drinking water systems is also possible. This accidental contamination is perhaps a more realistic threat for small utilities. Humans can unintentionally contaminate systems with pesticides, toxic industrial chemicals, or other materials, and various chemicals could enter the system through accidental backflow, breaks in pipes, or leaky joints. Systems can also be contaminated if metals, organic contaminants, or asbestos in pipe materials and linings are able to leach into the network (Murray et al., 2010). Contamination warning systems have been proposed as a cost-effective and reliable strategy to mitigate risks from both intentional and accidental contamination of the water supply.

Networks of sensors deployed around the system that are able to detect changes in water quality are a critical component of a CWS. Therefore, the majority of effort in CWS research has focused on developing methods to utilize water quality sensors as indicators to detect contamination in a system (McKenna et al., 2006). Because the extent of any monitoring system will be constrained by a limited budget, a great deal of effort is being placed on optimizing the placement of monitoring stations around the system (Janke et al., 2006). It is important to determine the optimal locations for sensors in a distribution system to maximize their ability to detect contamination and protect human health.

In recent years, several researchers have developed computer software for use in locating optimal water quality sensor placement in distribution systems. These include TEVA-SPOT as developed by the EPA (Berry et al., 2010), as well as products by several commercial vendors including KYPIPE (Schal et al., 2014). The major drawback with such algorithms is that they require an understanding of flow dynamics and how contaminants will behave in a system, necessitating use of a simulation-based analysis utilizing calibrated hydraulic and water quality models. Unfortunately, most small to medium sized utilities lack the financial resources or expertise to build water quality models of their network necessary to utilize such programs.

In recognition of this problem, several researchers have explored the use of simple heuristics to aid in determining the optimal location of sensors. A recent study by Xu et al. (2008) explored the use of two graphical network parameters defined as "betweeness centrality" and "receivability" as ways to assign scores to potential sensor sites. In a similar study, Isovitsch and VanBriesen (2008) looked at the use of "reachability" and “reachable average demand” parameters for prioritizing sensor locations. More recently, Chang et al., (2011) developed a rule-based expert system, and later expanded to a rule-based decision support system (2012), to generate sensor deployment strategies. While it does rely on a hydraulic simulation of the network to determine the flow fraction for each node in the network, it does not require the use of a complex optimization algorithm.

In the proposed study, results from applications of the Water Quality Sensor Placement Tool (Schal et al., 2014) to a range of water distribution systems (characterized as either branch, grid, or loop system) are used to develop regression equations that relate system characteristics (e.g. number of pumps, tanks, etc.) to the optimal location of a single water quality sensor as measured in relation to a critical tank location. Use of these equations along with a few simple rules for each type of system configuration (i.e. branch, grid or loop) then provide a general methodology for use in selecting a water quality sensor location for a small distribution system.

DEVELOPMENT OF GUIDANCE PROCEDURE

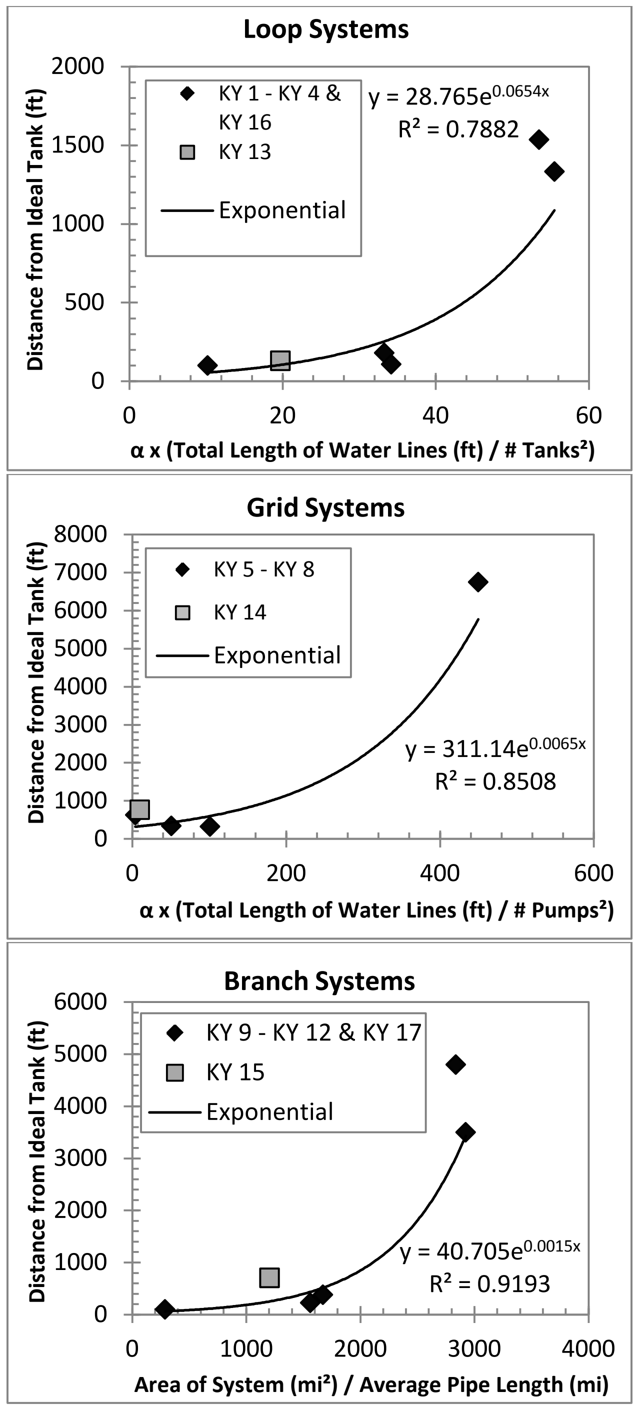
The model database utilized in this study consists of 15 system models representing real distribution systems located in Kentucky. Twelve models were evaluated using existing sensor placement software (Schal et al., 2014) to gather data used in development of the procedure, and three models were used for verification of the developed procedure. All models were given a name in the form KY #, and identifying information, such as the name of pumps or tanks, for the actual systems represented by the models was removed for security purposes. All system models used in this study can be classified by one of the three main system configurations: loop, grid, or branch. These configurations will be discussed further.

The Water Quality Sensor Placement Tool developed in KYPIPE was executed on the system models to collect data for this study. The sensor placement tool requires input of a hydraulic model and recommends sensor placement, for up to five sensors, based on minimizing time to detection. The tool recommends optimal locations for online sensors based on simple water quality analyses and enumeration of the travel times between all possible injection and sensor locations, resulting in sensor placement at locations that detect contamination events the fastest.

To execute a sensor placement simulation, a contamination scenario is required, and this is determined by the injection rate of the contaminant (in mg/min) and the total injection time (in hours). The baseline contamination scenario, where a contaminant was injected at 1000 mg/min for four hours, was used in the KYPIPE sensor placement tool to collect data for the average time to detection for possible sensor nodes in all 12 systems. This scenario was used because it represented a middle ground of all scenarios performed, and many other contamination scenarios resulted in identical sensor selection for the same network. After an initial analysis, two additional systems (i.e. KY16 and KY17) were added to the development database, so as to improve the regression equations that serve as a basis of the overall methodology.

Results from these executions in KYPIPE, specifically the average times to detection generated for each potential sensor node in the system, were used to develop the sensor placement guidance procedure. It was found that the nodes with the fastest times to detection were clustered around a particular storage tank in each system, referred to as the ideal tank (to be discussed further). It was desired to identify relationships between the critical distance from the ideal tank where the most optimal sensor nodes were located and various system parameters for each configuration. For example, the critical distance varied as a function of a parameter utilizing the total length of water lines and number of tanks in the network for the five systems in the loop configuration. Similar relationships were developed for the branch and grid configurations. Separate exponential equations were then fit through each of the data sets to provide an equation that relates the optimal sensor location as measured by the distance from the "ideal" tank. After an initial analysis, two additional systems (i.e. KY16 and KY17) were added to the development database, so as to improve the regression equations that serve as a basis of the overall methodology. The final regression equations are illustrated in Figure 1. Each plot shows the data points used to develop the exponential trend (black diamonds) and the exponential equation along with the actual distance from the ideal tank to the highest ranked node in the verification system (gray square). The verification systems will be further discussed.

Figure 1: Actual vs. Predicted Distance from Tank in Verification



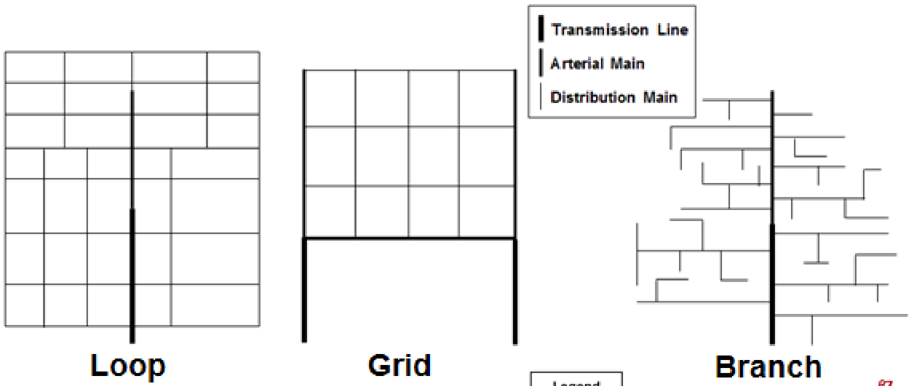
PROCEDURE FOR SENSOR PLACEMENT GUIDANCE

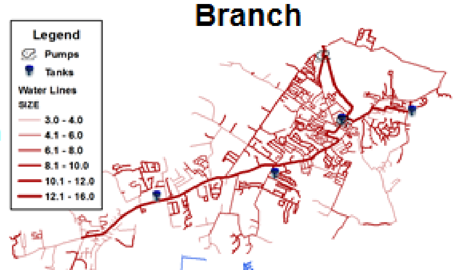
The proposed procedure requires three relatively simple steps which rely exclusively on geometric information about the system. No computer analyses are required. The first step requires the user to determine which general system configuration their system best matches: loop, grid, or branch configuration. This is an important step because the procedure for each system configuration follows the same general steps, but certain details and equations vary based on the type of configuration. The general procedure then selects an "ideal" tank. The ideal tank represents the tank in the network where the best sensor locations are theoretically near. Once the ideal tank is selected, certain system parameters are used to provide the user a recommended distance from the ideal tank that a water quality sensor should be placed, following the water lines. For grid and loop systems, the total length of water lines in the system is needed, along with the number of tanks in loop systems and number of pumps in grid systems. For branch systems, the average length of water lines in the system (in feet) is needed. The area of a circle drawn to encompass the entire system (drawn in step #1 during the ideal tank selection process) is also needed. The user should begin at the ideal tank and follow the water lines away from the tank the specified distance. A ruler and scaled map, or a map of the network showing the length of all pipes, should be used to execute this step. The sensor should be placed at the closest "node" to this point that is also feasible for deployment of a sensor.

It is possible that there will be multiple pathways as the optimal distance is measured from the ideal tank. This is a slight potential limitation of the method. If multiple pathways are possible at any point, the procedure includes rules to aid the user in selecting the best pathway. These rules should be followed in all situations if it is unclear which pathway following the pipes should be taken. This includes situations where there is more than one pipe connected directly to the ideal tank or if a single pipe connected directly to the tank later intersects with other pipes to create multiple pathways before the recommended distance is reached. The procedure is outlined in the following sections, along with an example of an executed procedure for a loop network.

Step 1: Determine the type of system configuration. In order to recommend guidance for the placement of one sensor in a small water distribution system, it is important to first determine if the system is in branch, loop, or grid configuration. Systems may appear to be a combination of different configurations, but networks should be classified strictly as one configuration based on which configuration characteristics are most prominent. Figure 2 may be used as a general visual guide to determine which configuration best describes a particular water distribution system.

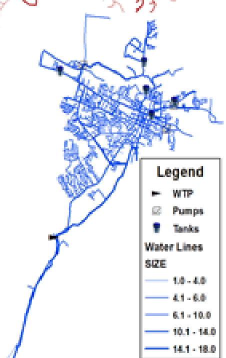
Figure 2. Determining Water Distribution System Configuration





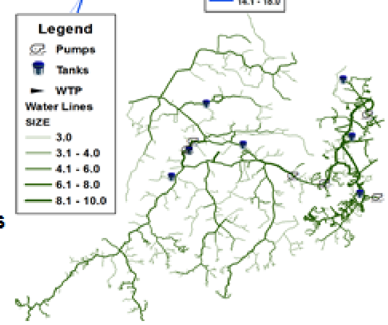
Loop

- Large transmission line through center of system
- Feeds smaller pipes located outward of center
- Small pipes connect at ends to main loop
- Common in municipal/densely populated areas
- Several paths from source to customer



Grid

- Can look similar to checkerboard
- Large pipes loop around outside of system
- Transitions to small pipes in interior
- Common in municipal/densely populated areas
- Several paths from source to customer



Branch

- Similar to tree branches
- Smaller pipes branch off centralized, larger pipes
- Numerous dead ends
- More pumps, tanks, and greater total length of pipes
- Sometimes only one path from source to customer
- Common in sparsely populated areas

Step 2: Identify the "ideal" tank. The next step of the procedure is used to identify the "ideal" tank. The user should assign a numerical score of one to each tank that best fits the criteria listed below for each system configuration. A scenario may occur where more than one tank best fits the criteria, and a score of one should be awarded to both tanks in this case. For example, one of the criteria specifies the tank located at the lowest ground elevation. If two tanks are located at the same elevation (although this would be uncommon), and the elevation is also the lowest of all tanks in the system, a point should be awarded to both tanks. At the end of the evaluation process, the tank with the highest number of points in the system is selected as the ideal tank. If there is a tie for the highest number of points, each configuration includes a guideline to break the tie. The procedure for tank selection for loop systems is shown in Figure 3.

Figure 3. Step 2: Ideal Tank Selection (Loop Systems)

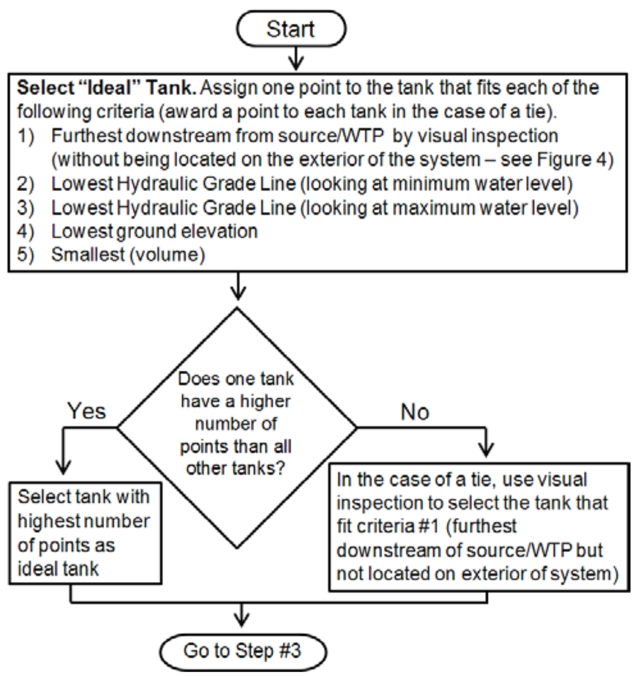
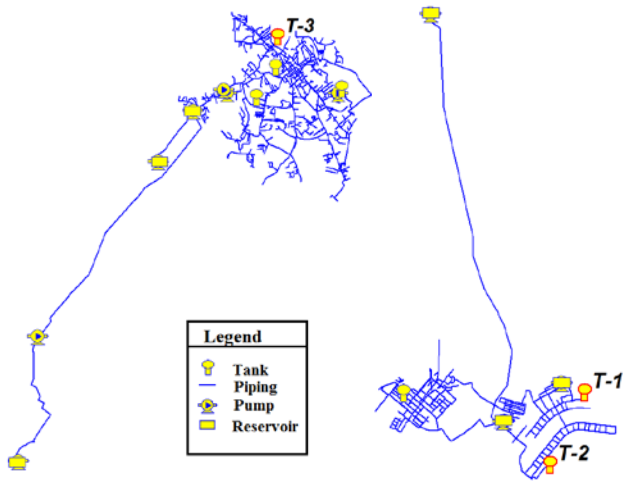


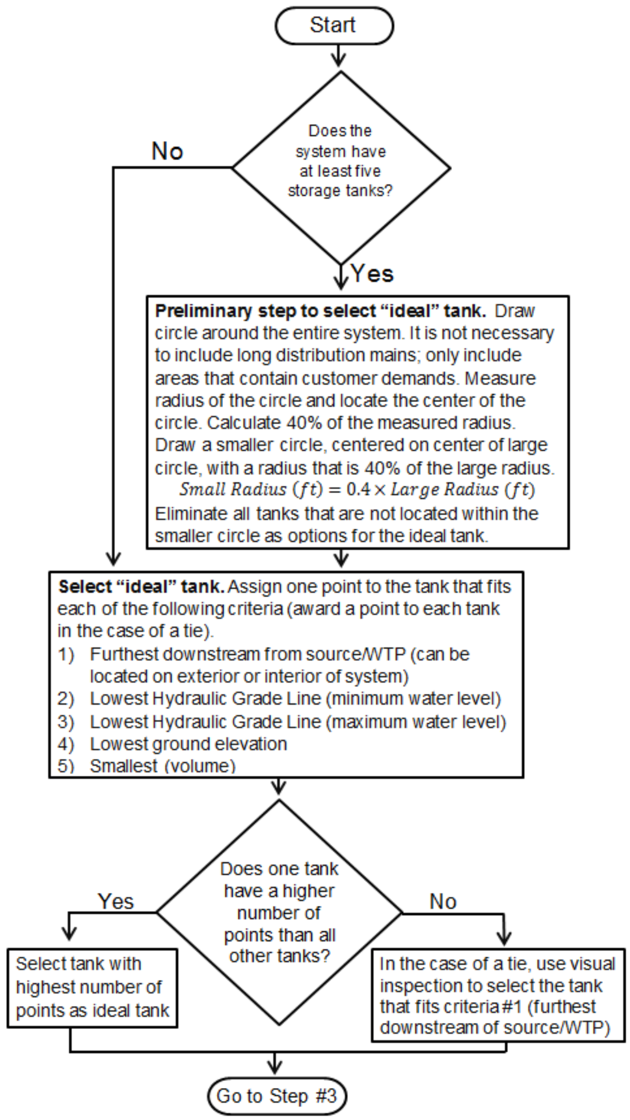
Figure 4 displays examples of tanks considered exterior (exterior tanks are highlighted and labeled, while interior tanks are not labeled with the tank name), which can serve as a tool in the tank selection step.

Figure 4. Examples of Exterior Tanks



The procedure for selection of the ideal tank in grid systems is shown in Figure 5. If the system has five or more tanks, a preliminary step is necessary in selecting the ideal tank.

Figure 5. Step 2: Ideal Tank Selection (Grid Systems)



This process for the branch systems is slightly more complex than for loop and grid systems; selection of the ideal tank requires several steps, shown in Figure 6. If a system contains more than 20 storage tanks, there is too much uncertainty in selecting the ideal tank. Therefore, the guidance procedure cannot be used to recommend sensor placement. The user should create a model using the KYPIPE software and execute the sensor placement tool. Figure 7 shows an example of a system with a distinct downtown area, which can serve as a tool in the tank selection step for branch systems.

Figure 6. Step 2: Ideal Tank Selection (Branch Systems)

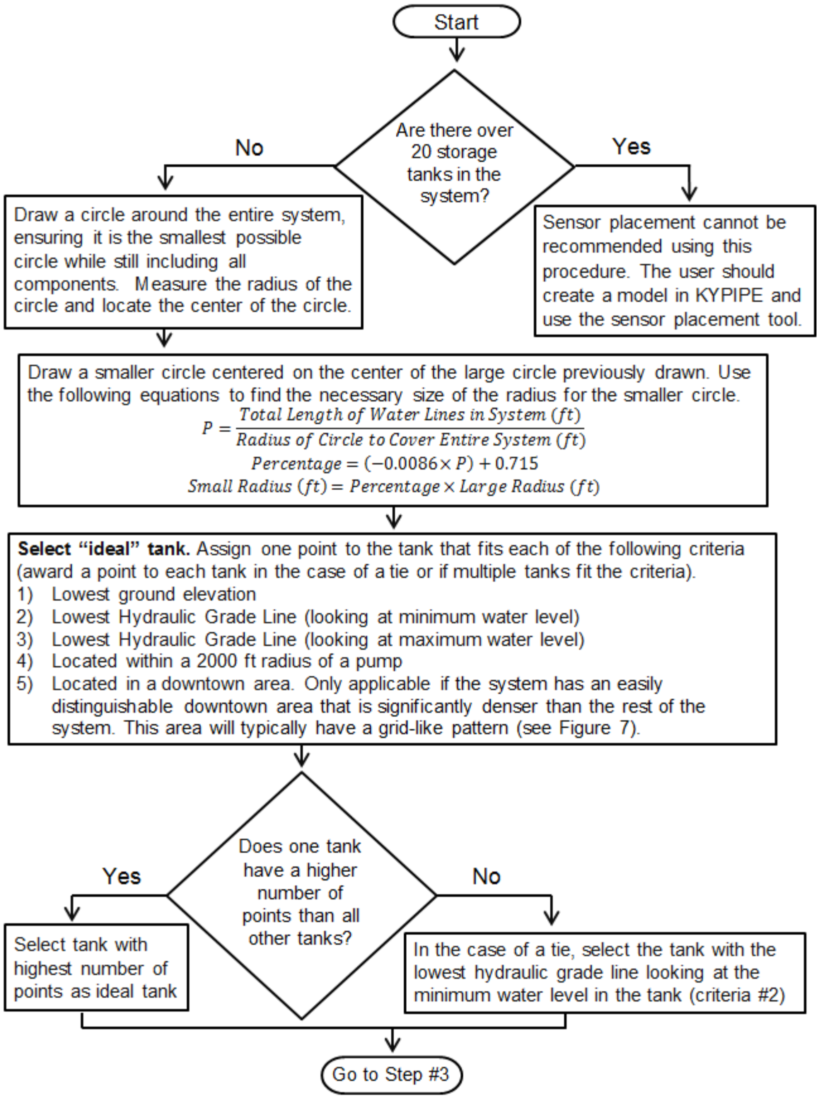
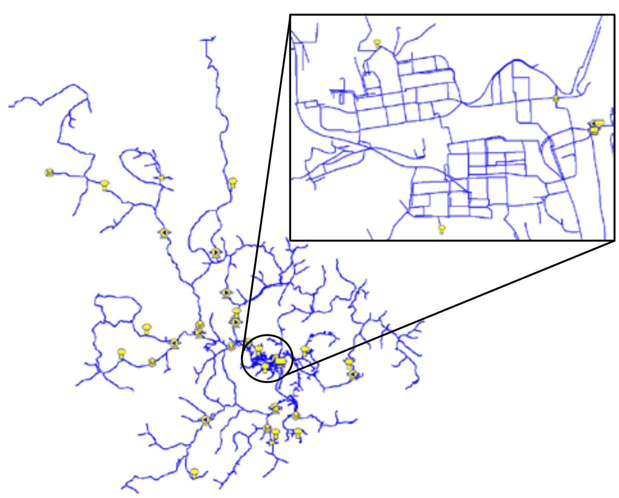


Figure 7. Example of Downtown Area (Branch)



Step 3: Determine the recommended distance from ideal tank. The last step of the simplistic sensor placement procedure uses a set of equations developed to provide the user a recommended distance from the ideal tank that a water quality sensor should be placed. The user should begin at the ideal tank and follow the water lines away from the tank the specified distance, placing the sensor at the closest node to this point that is also feasible for deployment of a sensor. Nodes are defined as the intersection of any pipes or a location where the pipe diameter or material changes. The sensor should be placed at the closest node to the recommended distance, instead of simply the location exactly at the recommended distance. This study found that better sensor locations (as measured by lower average times to detection) were located at points where multiple pipes intersected. Specifically, the general trend showed an increase in effectiveness as the number of pipes intersecting at the node increased. If the sensor is placed at a defined node, it will likely be more effective based on data generated in this study. The remainder of the procedure is shown in Figure 8, and Figure 9 shows examples of portions of a system where the location of a node is appropriate.

As mentioned, the flowchart includes rules to aid the user in selecting the best pathway if multiple pathways are possible moving away from the ideal tank. Figure 10 illustrates this concept. The ideal tank and the diameters of water lines are labeled; arrows are also included to show the correct pathway that should be followed. In the top portion of Figure 10, the first arrow selects the path that is in the opposite direction of the dead-end, and the second arrow follows the pipe with the larger diameter. In the bottom portion, the user would select the pathway containing the pipe with the largest diameter (marked with the black arrow).

Figure 8. Step #3 of Simplistic Procedure (All Systems)

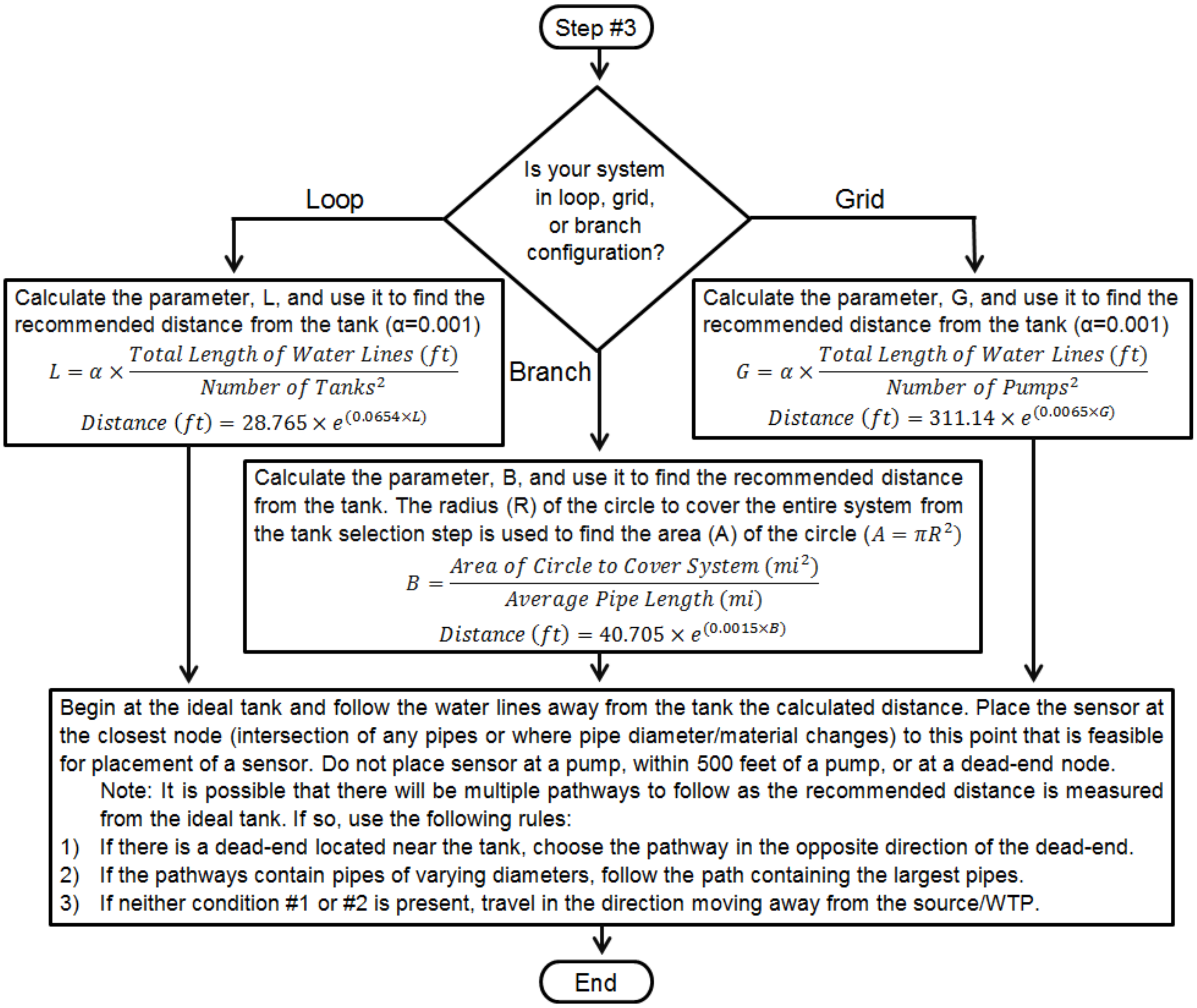


Figure 9. Examples of Nodes

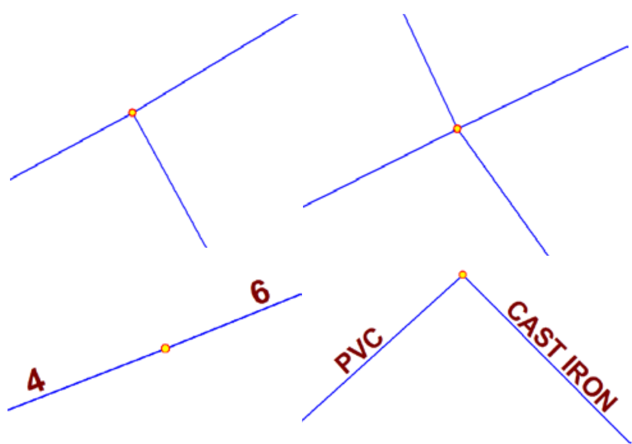


Figure 10. Selection of Pathway from Ideal Tank

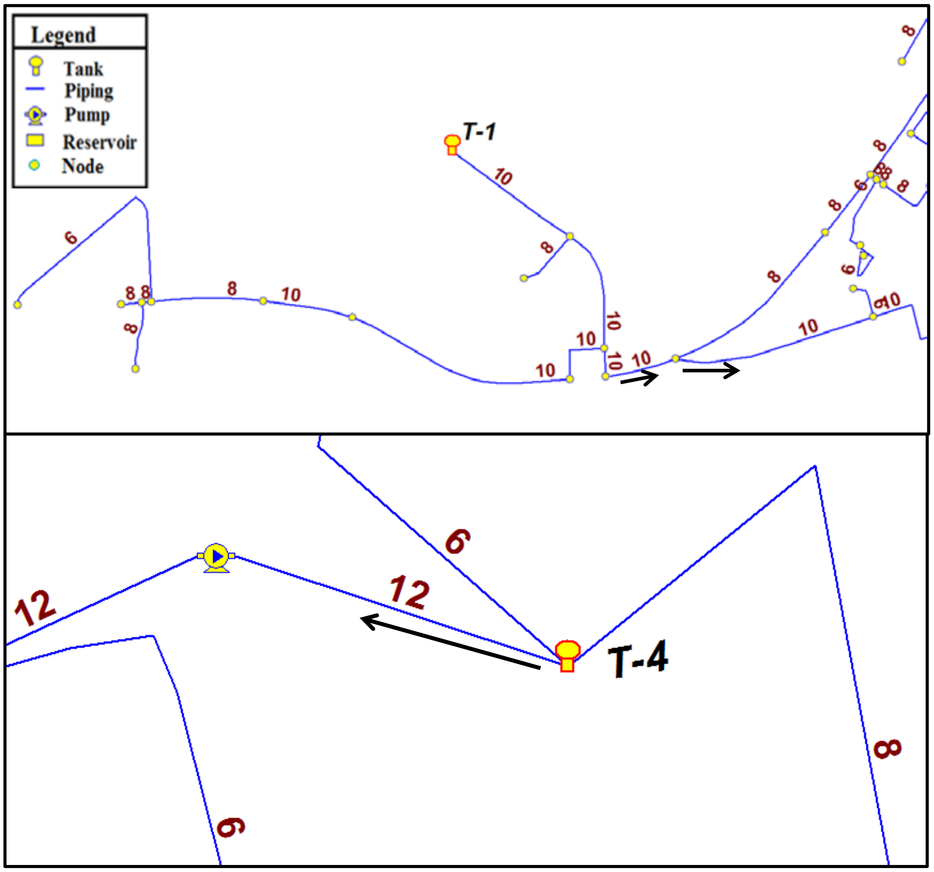
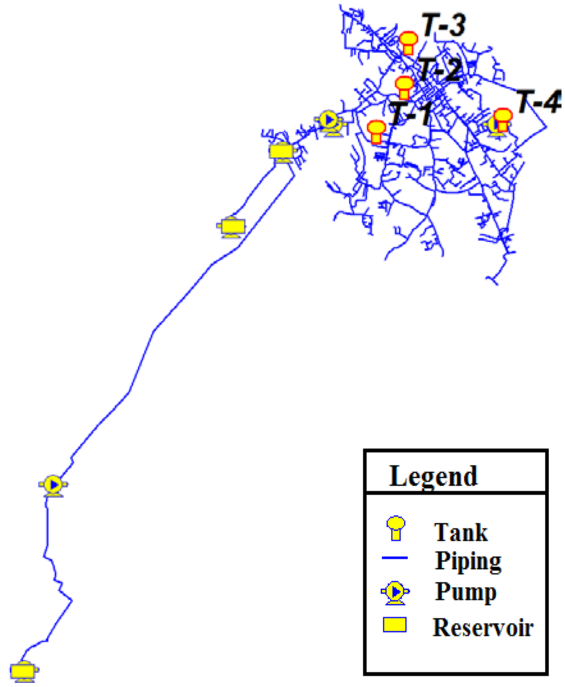


ILLUSTRATION OF THE METHODOLOGY

An illustration of the methodology for a loop system (i.e. KY 1 in Figure 11) is provided below. Figure 11 shows all four tanks in KY 1 that are possibilities for the ideal tank. The list of criteria, along with the tank awarded a point for each criterion, is outlined below. Table 1 shows data for all tanks in the system, including the total number of points each tank was awarded in step #1.

Figure 11. Example of Ideal Tank Selection (KY 1)



1) Furthest downstream of source/WTP without being located on exterior of system: T-4. Visual inspection of Figure 11 was used to determine the tank that best fit this criterion. Both T-3 and T-4 appear to be far downstream from the sources and WTP. However, T-3 is located on the exterior of the system and T-4 appears to be slightly further away from the sources. T-4 is awarded the point for this criterion.
2) Lowest HGL (looking at minimum water level in tank): T-4
3) Lowest HGL (looking at maximum water level in tank): T-4
4) Lowest ground elevation: T-4
5) Smallest (in volume): T-4 and T-3

Table 1. Tank Information (KY 1)

Tank	Ground Elevation (ft)	HGL (max level - ft)	HGL (min level -ft)	Diameter (ft)	Volume (ft^3)	Located furthest downstream?	Interior Location?	Total Points
T-1	1344.8	1465	1430	99	269419	No	Yes	0
T-2	1338.9	1450	1430	68	72634	No	Yes	0
T-3	1348.3	1465	1440	60	70686	No	No	1
T-4	1232.8	1425	1400	60	70686	Yes	Yes	5

T-4 was awarded five points total, which was significantly higher than any other tank. Therefore, T-4 was selected as the ideal tank.

Once the ideal tank is selected (i.e. T-4), the total length of water lines in the system (in feet) along with the number of tanks in the system is needed. The parameter, L, was calculated using the equation specified in Figure 8 for loop systems (shown below in Equation 1). In this equation, α = 0.001.

$$L = \alpha \times \left(\frac{Total\ Length\ of\ Water\ Lines\ in\ System\ (ft)}{Number\ of\ Tanks^2} \right) = 0.001 \times \left(\frac{499535\ ft}{3^2} \right) = 55.50 \quad \textbf{(1)}$$

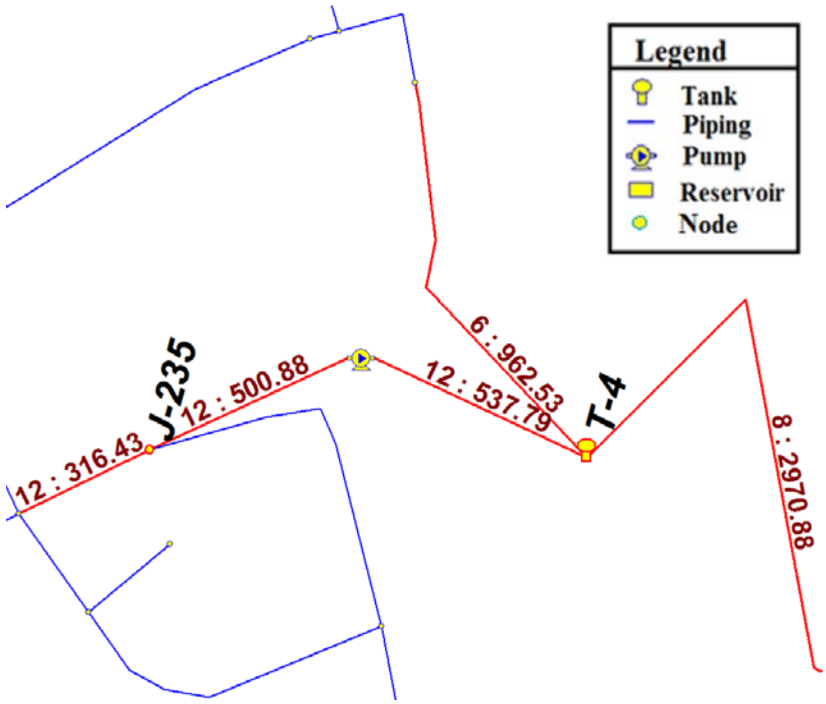
The parameter, L, was then used in Equation 2 to find the recommended distance from the tank.

$$Distance\,(ft) = 28.765 \times e^{(0.0654 \times 55.50)} = 1084.48\ ft \quad \textbf{(2)}$$

The recommended distance from the ideal tank that a water quality sensor should be placed is 1084.5 feet (following the water lines). Observing the configuration of KY 1 shown in Figure 12, there are three different pipes connected to T-4. The user is faced with the challenge of selecting the best pathway to follow when moving away from T-4. None of the three options led directly to a dead-end, so this rule cannot be used to eliminate a possibility. Next, the pipe diameters for the three different pathways were examined. There were a 6'', 8'', and a 12'' pipe connected to the ideal tank. Because one path had a larger pipe than the other pathways, the path containing the largest pipe was followed.

The node located closest to the recommended distance away from the tank, following the largest pipe, was J-235. The recommended distance was 1084.48 feet, and J-235 was located 1015.92 feet away from T-4. Therefore, J-235 was selected as the recommended location for a sensor node. The selected node is labeled in Figure 12, along with the pipe diameter and length of the water lines connected to T-4 (diameters listed first followed by length, separated by a colon).

Figure 12. Example of Selecting Sensor Node (KY 1)



VERIFICATION OF SENSOR PLACEMENT GUIDANCE

The simple sensor placement procedure outlined in this study was developed using data from 12 water distribution system models (KY 1- KY 12) along with data from the two additional networks (KY 16 and KY 17). These systems included five networks in either the loop and branch configuration and four systems in the grid configuration. To verify the effectiveness of the proposed sensor placement guidance, the procedure was tested on three additional system models: KY 13, KY 14, and KY 15 representing a loop, grid, and branch system, respectively. The KYPIPE sensor placement tool was executed on these three systems for the scenario of a contaminant injected for four hours at a rate of 1000 mg/min, identical to the scenario used to gather data with the system models for development of the procedure. Results from the KYPIPE sensor placement tool were then compared with the solution determined using the outlined procedure to verify the effectiveness of the sensor placement guidance developed in this study.

The KYPIPE sensor placement tool considers all nodes (including tanks, pumps, reservoirs, and junctions) except dead-end nodes as possible sensor locations. The sensor placement guidance developed in this study does not consider tanks, pumps, or reservoirs as potential sensor locations. Therefore, the values reported for the number of possible sensor nodes, along with rankings and average times to detection, will reflect possible locations in the guidance procedure.

The ideal node selected using the proposed procedure was compared to the sensor location chosen by KYPIPE. Table 2 displays the nodes selected by each method and their respective average times to detection (generated by KYPIPE), the ranking of the node selected by the guidance procedure (based off times to detection), and the differences in time to detection.

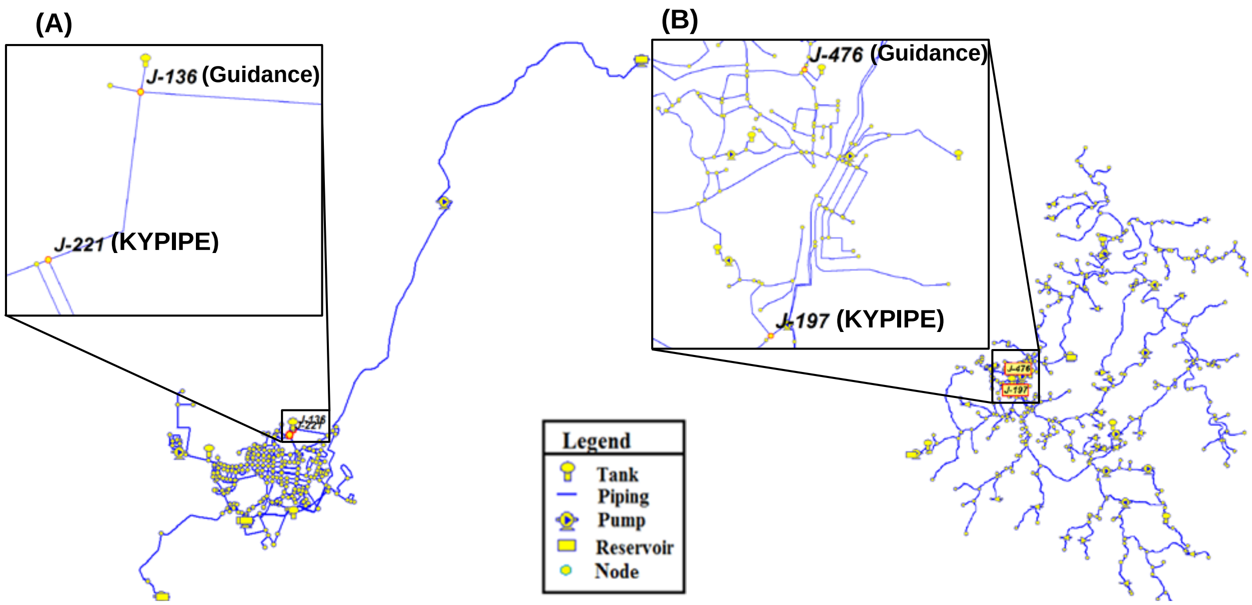
Table 2. Comparison of Sensor Selection between KYPIPE and Simple Procedure

System	Possible Sensor Nodes	KYPIPE		Simple Procedure			Time Difference (hr)	Percent Difference in Times
		Selected Node	Time to Detection (hr)	Selected Node	Time to Detection (hr)	Ranking		
KY 13	452	J-516	16.75	J-516	16.75	1	0	0%
KY 14	277	J-221	15.95	J-136	16.34	3	0.39	2.4%
KY 15	399	J-197	17.15	J-476	17.72	31	0.57	3.3%

For the loop configured system (KY 13), the KYPIPE sensor placement tool and the simple sensor placement guidance procedure selected the same node, J-516, as the most effective sensor location. Comparing results for the grid system (KY 14) showed that KYPIPE selected J-221 and the guidance procedure chose J-136. Based on times to detection produced by the KYPIPE sensor placement tool, J-136 was ranked third out of the 277 possible sensor nodes. The location of both nodes can be viewed in Figure 13.

To verify the effectiveness of the procedure for branch configured systems, the KYPIPE sensor placement tool was executed on KY 15, and J-197 was chosen as the best location for a water quality sensor. The guidance procedure selected J-476 as the most effective sensor location, and this node was ranked 31st out of a possible 399 nodes (based on the times to detection provided by KYPIPE). The spatial variation in the location of the two nodes is shown in Figure 13.

Figure 13. **Sensor Location Comparison: (A) KY 14; (B) KY 15**



The accuracy of the simple procedure for sensor placement can also be evaluated by examining the plots in Figure 1. Each plot shows the data points used to develop the exponential trend (black diamonds) and the actual distance from the ideal tank to the highest ranked node in the verification system (gray square). In all three configurations, the actual data for the verification system is fairly close to the predicted values found from the exponential equation.

ANALYSIS AND DISCUSSION

The verification study showed that the graphical sensor placement procedure performed well. The procedure developed for the loop system selected the most ideal node, as compared with data from the KYPIPE sensor placement tool. Verification performed on the grid system showed that the simple procedure selected the node ranked third out of a possible 277 sensor nodes based on times to detection generated by KYPIPE. The node chosen by the procedure was located in very close proximity to the highest ranked node and the percent difference in average time to detection was only 2.4% (0.39 hours). Therefore, the guidance developed in this study did an excellent job of selecting an effective sensor location for the grid system.

For verification of the procedure for branch configured systems, the developed procedure chose J-476 as the ideal sensor node and the KYPIPE sensor placement tool selected J-197. J-476 was ranked 31st out of a possible 399 nodes, based on the times to detection provided by KYPIPE. The time to detection of the highest ranked node was 17.15 hours, and the time to detection for J-476 was 17.72 hours, resulting in a percent difference in times of only 3.3% (0.57 hours).

The spatial variation in the location of the nodes selected by each method in KY 15 can be viewed in Figure 13. Observing the entire system, the nodes seem to be located in fairly close proximity. However, the zoomed portion of the figure explains why the guidance procedure did not select the most ideal node. During step #1 of the procedure, the tank located directly next to J-476 (T-4) was selected as the ideal tank. However, data for average times to detection generated by KYPIPE revealed that the nodes with the fastest times to detection were actually located near T-6 (located slightly northwest of J-197). The procedure did not select the tank surrounded by the top ranked sensor nodes as the ideal tank, but it was able to select a tank in close proximity that was surrounded by nodes with times to detection that were close to the fastest time. Although the procedure was not successful in selecting what would have been considered the most ideal tank, it did select a node in close proximity to the ideal node and with a low time to detection.

Distribution systems classified in the branch configuration typically have more storage tanks (or standpipes) than loop or grid systems. This makes it slightly more difficult for the developed procedure to select the tank that is surrounded by the nodes with the fastest times to detection. This is considered a slight limitation of the guidance procedure for branch configured systems. However, the verification showed that even if the most ideal tank is not chosen in the tank selection process, the guidance will still select a tank that is surrounded by nodes with relatively fast times to detection. The verification study proved that the guidance procedure for the placement of one sensor behaved well compared to the KYPIPE sensor placement tool.

SUMMARY AND CONCLUSIONS

Because increased focus has been directed at protecting the water infrastructure in recent years, various software been developed to assist utilities in identifying the optimal placement for water quality sensors. These water quality sensors are in support of Contamination Warning Systems that aim to deliver early detection of a contamination event in a drinking water system. However, many of the previously developed methods utilize information about flow dynamics in a system. This requires calibrated hydraulic and water quality models of the system, and small utilities typically do not have the financial resources or expertise to build these models. This research aimed to develop a simple graphical procedure, specifically designed for use by utility managers, which will recommend near optimal sensor placement without the need for a hydraulic model or complicated algorithm.

The procedure presented in this study does not require information about flow dynamics or how a contaminant will behave in the system. It simply uses basic information about the geometry of the system, such as the total length of water lines, average pipe length, and number of tanks in the system. While not as reliable as software like TEVA-SPOT or KYPIPE, the proposed methods should provide a useful tool for small utilities with limited resources.

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