A Simplified Procedure for Sensor Placement Guidance for Small Utilities

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Abstract

Water distribution systems are vulnerable to intentional, along with accidental, contamination of the water supply. Contamination warning systems have been developed with the goal of providing an early detection of contamination. A network of water quality sensors deployed in a system can alert an operator of a potential contamination event, but these sensors must be placed in locations that maximize their ability to detect contaminates. Robust models and algorithms have been developed to aid in the placement of sensors, but many of these methods require calibrated hydraulic/water quality models of the system. Many small utilities do not possess the financial resources or expertise to build calibrated models. Because of such limitations, a simple procedure is proposed to recommend optimal placement of a sensor without the need for a model or complicated algorithm. The procedure uses simple information about the geometry of the system and does not require explicit information about flow dynamics. While the proposed simplified method does not claim to be as reliable as currently available sensor placement software, it should accomplish the goal to provide an effective solution for small utilities with limited technical and financial resources. This paper outlines the procedure to guide utilities in the placement of a water quality sensor along with a verification study.

Introduction

In recent years, terrorism threats has led to increased attention on the security of infrastructure systems in the U.S. and worldwide, and part of this goal aims to protect the water infrastructure. Water distribution systems are considered to be vulnerable to intentional, along with accidental, contamination because they have a large spatial distribution and multiple points of access. Many systems lack monitoring and security systems, which greatly increases the risk and potential danger associated with an attack (Hart and Murray, 2010). In an effort to mitigate the risks from contamination of a water supply, contamination warning systems (CWS) have been proposed as a cost-effective and reliable strategy.

The goal of a CWS is to provide an early detection of contamination in order to reduce public health impacts and economic loss (Janke et al., 2006). Perhaps the most critical component of CWS, classified as online quality monitoring, involves sensors that can assess the quality of water in the distribution system and alert an operator of a potential contamination event. These water quality sensors must be placed in locations that maximize their ability to detect contamination events, so utilities developing monitoring systems are faced with the decision of what locations are optimal for deployment of these sensors (McKenna et al., 2006).

A major goal in the effort to solve water security problems is to identify optimal water quality sensor deployment in distribution systems. Robust models and algorithms have been developed to achieve effective water quality monitoring (Chang et al., 2011). However, many of these developed methods require an understanding of flow dynamics and how contaminants will behave in a system, which can be observed with a simulation-based analysis using calibrated hydraulic and water quality models. For example, the TEVA-SPOT software (Threat Ensemble Vulnerability Assessment Sensor Placement Optimization Tool) has been developed to analyze the vulnerability of drinking water distribution networks and aid utilities in the design of sensor networks. A hydraulic and water quality model is setup in EPANET, and this is used as input for TEVA-SPOT to recommend sensor placement based on a variety of user defined objectives (Murray et al., 2008).

Although TEVA-SPOT is a useful resource for sensor placement, many utilities do not possess water quality models of their system because of the significant calibration requirements needed to build an effective model. Small utilities typically do not have the financial resources or expertise to build these models. Even if a model can be created, the computational requirements for computing contaminant concentrations from injection at all locations in the system can be extensive.

Because of such limitations, a simple procedure is proposed for use in the optimal placement of a water quality sensor without the use of a model or more complicated algorithm. The procedure uses simple information about the geometry of the system and does not require any information about flow dynamics. Although this simplified method may not be as accurate as TEVA-SPOT, it should provide an effective solution for small utilities with limited financial and technical resources. This study outlines the procedure developed to recommend sensor placement along with a verification study to demonstrate the method will be an effective tool for small utilities.

Current Trends in Sensor Placement

Following the initial development of TEVA-SPOT, several researchers have investigated the possible use of simpler approaches or heuristics for use in water quality sensor placement. Such methods have included the use of general rules and heuristics as well as methods that incorporate information about the flow distribution within a network.

Demand and Reachability

A study by Isovitsch and VanBriesen (2008) looked at the spatial trends in sensor placement determined by optimization methods. The authors caution that they believe sensor placement is likely dependent on network hydraulics, but the goal of their spatial analysis is to improve understanding of sensor network design criteria. The average nearest neighbor (ANN) tool is used to determine the degree of clustering among nodes by measuring the extent to which the spatial distribution of nodes differs from a randomly distributed set. The spatial autocorrelation tool aims to measure the underlying pattern between nodes based on their location and provides information about how clustered, random, or dispersed the data are. In the study, sensor placement was determined using an optimization method that accounted for time to detection, along with four other objectives, for four scenarios. Results from the average nearest neighbor analysis showed that sensor locations were clustered (with a less than 1 percent likelihood that the pattern could be the result of random chance), and the first sensors placed were more intensely clustered.

The authors hypothesized that “average demand”, “reachability”, and “reachable average demand” may be an effective indicator of optimal sensor placement. Reachability is the number of nodes in the network to which water can flow from the node in question, and reachable average demand represents the total demand for all nodes that are reachable from the node in question. There was not an obvious correlation present between sensor placement and these parameters when looking at all cases and scenarios together. However, when the systems were divided according to objective, some patterns were observed. A statistically significant dependency was found between sensor placement and high average demand for the objective functions time to detection and detection likelihood. When examining reachability of selected sensor nodes, the optimal nodes had low reachability for the objectives of expected time to detection and detection likelihood. Similar results were observed for average reachable demand.

Betweenness Centrality and Receivability

A study by Xu et al. (2008) simplifies the sensor placement problem by applying a graph-theoretic approach, which eliminates the need for a calibrated water quality model. An undirected graph represents the physical structure of a water distribution network and does not require hydraulic information about the system. This helps shed light on identifying structurally important nodes, which may have implications on the optimal placement of sensors. A parameter called “betweenness centrality” is used to define the centrality of a node in terms of the degree to which the node is located on the shortest path between other sets of nodes. Nodes with high betweenness centrality lie on the path of many pairs of other nodes, and these nodes would also be between many potential upstream contamination events and downstream receptor populations. Therefore, the authors argue that nodes with high betweenness centrality would be potential locations for sensors. It was noted that nodes with high betweenness centrality tend to cluster in the network.

Xu et al. (2008) also utilized the concept of “receivability”, used to describe the set and number of nodes that have paths to the measured node in a graph. This concept is developed from reachability. The reachability concept says that if there is one or more paths from node i to node j, then node j is reachable from node i and node i is receivable to node j. Receivability is able to measure the capability of a node to detect contamination events; sensors located at nodes with high receivability should detect more contamination events.

Rule-Based Expert System

A study by Chang et al. (2011) worked to develop a rule-based expert system (RBES) to generate sensor deployment methods without the computational burden typically encountered with optimization methods. The RBES utilizes an “accessibility rule” and a “complexity rule” to achieve the goal of addressing the complexity of the system and reducing the computer runtime while achieving the same level of robustness.

The accessibility rule utilizes results from a hydraulic simulation to determine the flow fraction for nodes in the network. The flow fraction is found with the flow from the main pipeline, a pipe with a larger diameter at each node, and the flow in a secondary pipeline, a pipe with a smaller diameter than the main pipe. A higher flow fraction means that the population density downstream of the node is higher because of the higher baseline demand in the downstream nodes (Chang et al., 2011). Because flow in a pipe is driven by the downstream water demand, the flow fraction can also be assumed as an index used to estimate the percentage of population that could be affected in the case of a contamination event (Chang et al., 2012a). The accessibility rule is used to rank the nodes from highest to lowest flow fraction in the system, and the design objective of this rule is to maximize flow fraction.

The complexity rule classifies nodes in the distribution system as inner nodes or path nodes. A path node has one or more pipes connected to the main pipe (junction with three or more pipes connected to it), and an inner node is located between two path nodes (maximum of two pipes connected at the junction). The complexity rule determines the number of inner nodes with a hydraulic connection to the path node systematically and deconstructs the node structure configuration to account for a larger population that could possibly be affected by a contamination event (Chang et al., 2011). An effective radius for each path node is calculated by dividing the summation of all pipe distances from a path node to each inner node by the number of inner nodes for each path node. The path nodes are then ranked from the highest number of inner nodes to the lowest and optimal sensor locations are selected as path nodes with the highest number of inner nodes (Chang et al., 2012a).

Rule-Based Decision Support System

Chang et al. (2012a) expanded this concept to a rule-based decision support system (RBDSS), which utilizes the same complexity and accessibility rules. The RBDSS expands the node classification concept to derive an effective radius. This improved complexity rule was developed to adjust for a large-scale network with a large number of inner nodes, and it can also be used to improve analysis of small systems. The improved complexity rule will cause sensor locations to be closer to highly populated areas and improve performance with design objectives. To find the effective radius for each node in the system, the distances from the pipe connecting the node of interest to its hydraulically connected neighbors in all directions were calculated. The number of nodes within the effective radius is counted, and the nodes are ranked in descending order based on the inner nodes and path nodes counted (Chang et al., 2012a).

Further work by Chang et al. (2012b) expanded the RBDSS to include an “intensity rule”. The intensity rule focuses on the concentration of contaminants in the system, and its goal is to ensure that the concentrations of potential contaminants remain under MCLs. Nodes are ranked from highest to lowest based on how much they exceed the MCLs at any point during the day. Nodes that exceed the MCLs are ranked highest, and the top ranked nodes are chosen as sensor locations (Chang et al., 2012b). Based on the intensity rule, the location with the highest population density is selected as a sensor location more often since higher exposure levels occur along the main pipe and tanks. This was consistent with results of the accessibility and complexity rules, because flow fractions in these areas should be higher and the number of inner nodes should be picked up more often (Chang et al., 2012a).

The Current Study

The goal of contamination warning systems is to reduce the exposed population to the contaminant and reduce contaminated water volume. One way to achieve this goal is by placing monitoring sensors at locations that minimize the time to detection with high reliability. Using this objective, an optimal water quality monitoring sensor location was determined for 12 different water distribution systems from Kentucky (Jolly et al., 2013). The optimal sensor locations were determined using a sensor placement algorithm that was embedded within a commercially available water distribution software package (Schal et al., 2013). The algorithm uses a complete enumeration optimization scheme coupled with the use of EPANET for both hydraulic and water quality analyses.

Contamination scenarios were created using three different general scenarios: fixed amount, fixed rate, and fixed time. Each general scenario was comprised of five specific sets of an injection rate and total injection time. A baseline scenario, where a contaminant was injected at 1000 mg/min for four hours, was included in all three general scenarios. Once the optimal sensor locations were obtained for each system, general trends or guidelines were sought on the basis of the type of system configuration (i.e. branch, loop, or grid), the proximity of the sensor to particular storage tanks, other system parameters, etc.

General Procedure for Sensor Placement Guidance

Based on the sensor placement results for the model database, general sensor placement guidelines were developed based on the type of system configuration (i.e. branch, loop, or grid). As a result, the first step in the proposed methodology was to determine the type of system configuration. The next step in the procedure is to select an "ideal" tank. The ideal tank will be one where the best sensor locations are theoretically near. The next major step in the procedure involves the creation of a circle of influence around the ideal tank, and all nodes located within the circle are considered possible sensor locations. The purpose of drawing the circle around one tank in the system is to drastically reduce the number of possible sensor locations. This centers the continued process on a small group of nodes, making the next step manageable for a utility manager and eliminating many options that are most likely not effective sensor locations.

The remaining steps are identical for all three system configurations. Easily measurable parameters are collected for every node within the circle, and a new parameter is computed using a combination of parameters. The nodes are arranged in increasing order of the parameter, which results in a list of possible sensor locations ranked in the order of effectiveness. The general description of each step is first outlined, and the specific procedure to be followed for each system configuration follows in a series of flowcharts.

Determine the 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 a branch, loop, or grid configuration. Many systems are a combination of different configurations. However, for the purposes of this research, all systems were classified strictly as one configuration based on which configuration characteristics were most prominent.

A system in the branch configuration resembles a tree with its network of branches. Pipes with small diameters branch off large, centralized pipes similar to how smaller limbs branch off the thick trunk of a tree. The large, central transmission lines typically carry high flows, and lower flows are experienced in distribution mains as pipe diameters decrease further away from the center of the system. In the geometric configuration of branch systems, water can theoretically only take one path from the source to customers (National Research Council, 2006). Branch systems are frequently present in rural areas where the service area is large, but the customers are not as densely populated. Consumers in the far branches especially are spaced far apart from each other. Because branch systems are more spread out, they typically contain more pumps, tanks, and a greater total length of water lines. However, the average diameter of pipes in branch systems is typically smaller.

Grid systems contain a large, centralized transmission line that feeds smaller lines. The central pipe supplies high flows from the source through the middle of the system, and this high flow is distributed to smaller pipes that convey lower flows moving outward from the center. These smaller lines also typically connect at each end into the main loop. The water lines in grid systems are sometimes laid out to resemble a checkerboard (Von Huben, 2005). Grid and loop systems share similar characteristics, as both systems contain these connected loops of pipelines, allowing several pathways that the water can flow from the source to customers. In contrast to grid systems, the larger water lines (that convey the greatest flow) in loop systems create a loop around the outside of the network. The system then transitions to smaller pipes in the interior of the system. Pipe sizes usually decrease as the distance away from the supply source increases (Von Huben, 2005). Both loop and grid system configurations are commonly used in large municipal areas or densely populated systems (U.S. Environmental Protection Agency, 2008). An example of a distribution system in branch, grid, and loop configuration is shown in Figure 1.

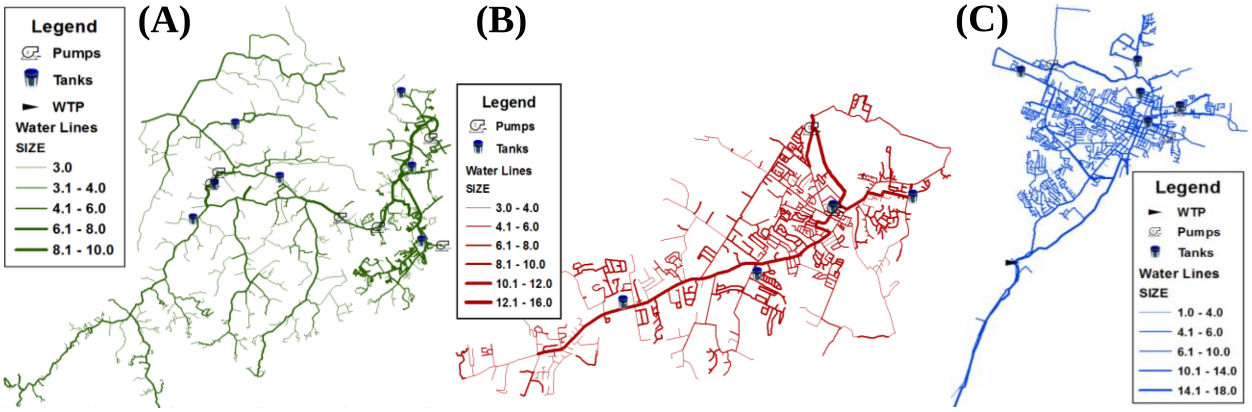

Figure 1. System Configurations: (A) Branch; (B) Grid; (C) Loop

Select the Ideal Tank

The second step of the procedure is to select the "ideal" tank. A point is assigned to each tank that best fits the selection criteria associated with each type of system configuration. In the case where more than one tank best fits the criteria, a point is awarded for both tanks. For example, one of the criteria for the loop and grid system specifies the tank with the smallest volume. If two tanks are equal in volume, and the volume is also the smallest of all tanks in the system, a point should be awarded to both tanks. 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 has an established guideline to break the tie. The procedure for tank selection in grid systems is shown in Figure 2.

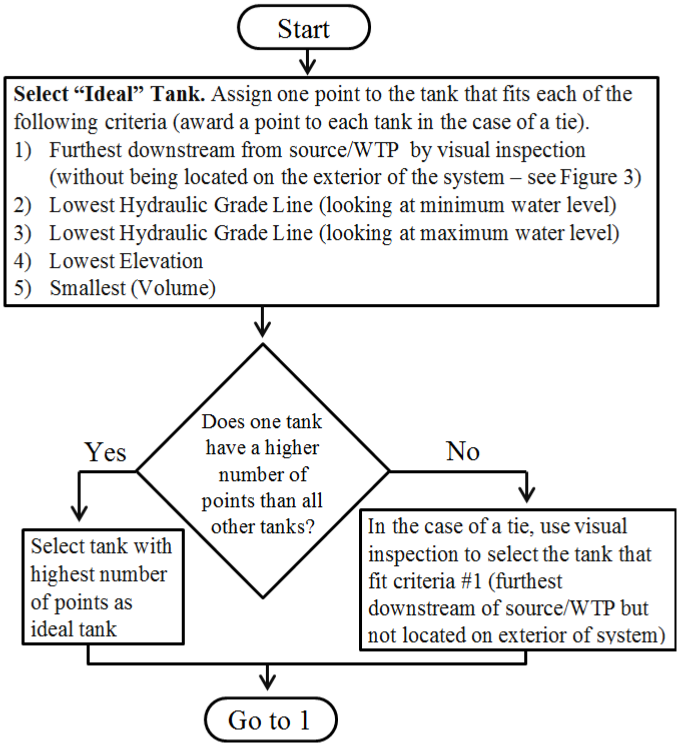

Figure 2. Ideal Tank Selection (Grid Systems)

Figure 3 displays examples of tanks considered exterior, which can serve as a tool in the tank selection step.

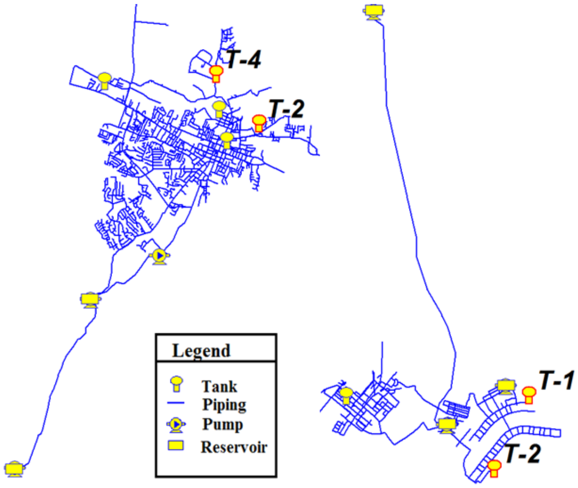

Figure 3. Examples of Exterior Tanks

The procedure for selection of the ideal tank in loop systems is shown in Figure 4. If the system has five or more tanks, a preliminary step is necessary in selecting the ideal tank.

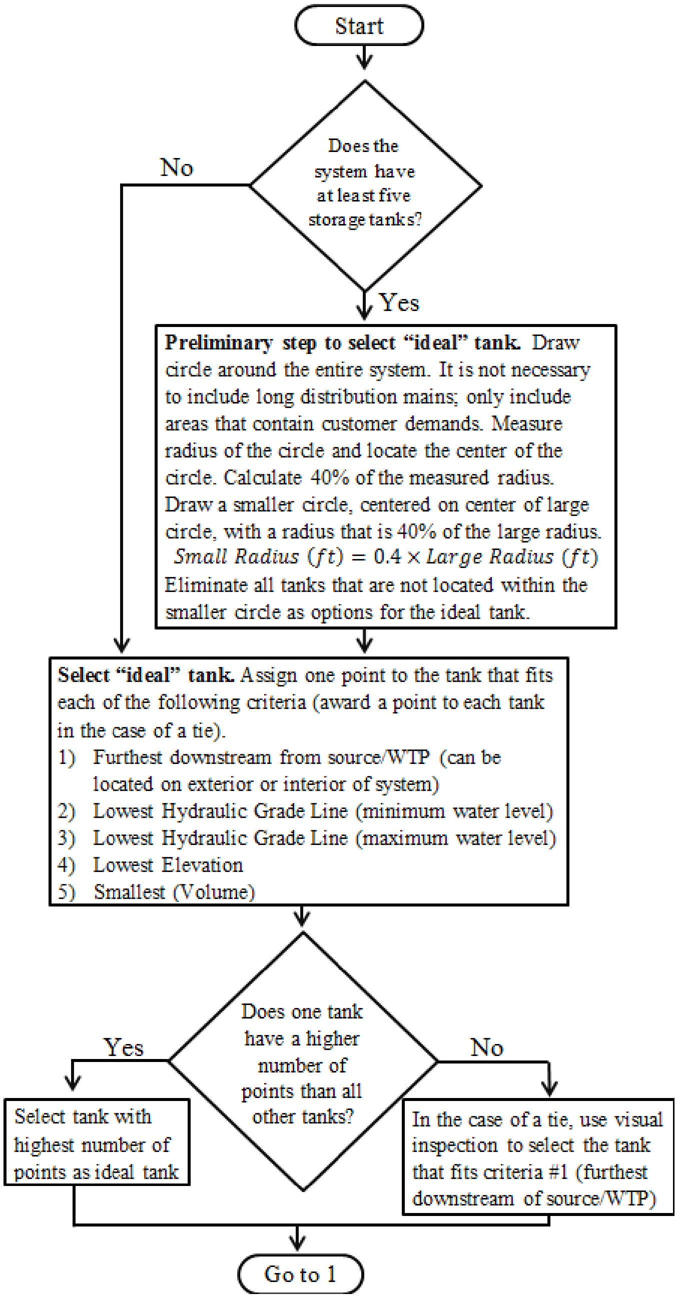

Figure 4. Ideal Tank Selection (Loop Systems)

The process for ideal tank selection in branch systems is slightly more complex and requires several steps, shown in Figure 5. If a system contains greater than 20 storage tanks, there is too much uncertainty in selecting the ideal tank, and the guidance procedure cannot be used to recommend sensor placement. In this case, the user can either eliminate some of the tanks from consideration or fall back on using one of the currently available sensor placement tools (e.g. TEVA-SPOT, KYPIPE, etc.). Figure 6 shows an example of a system with an easily distinguishable downtown area, which can serve as a tool in the tank selection step.

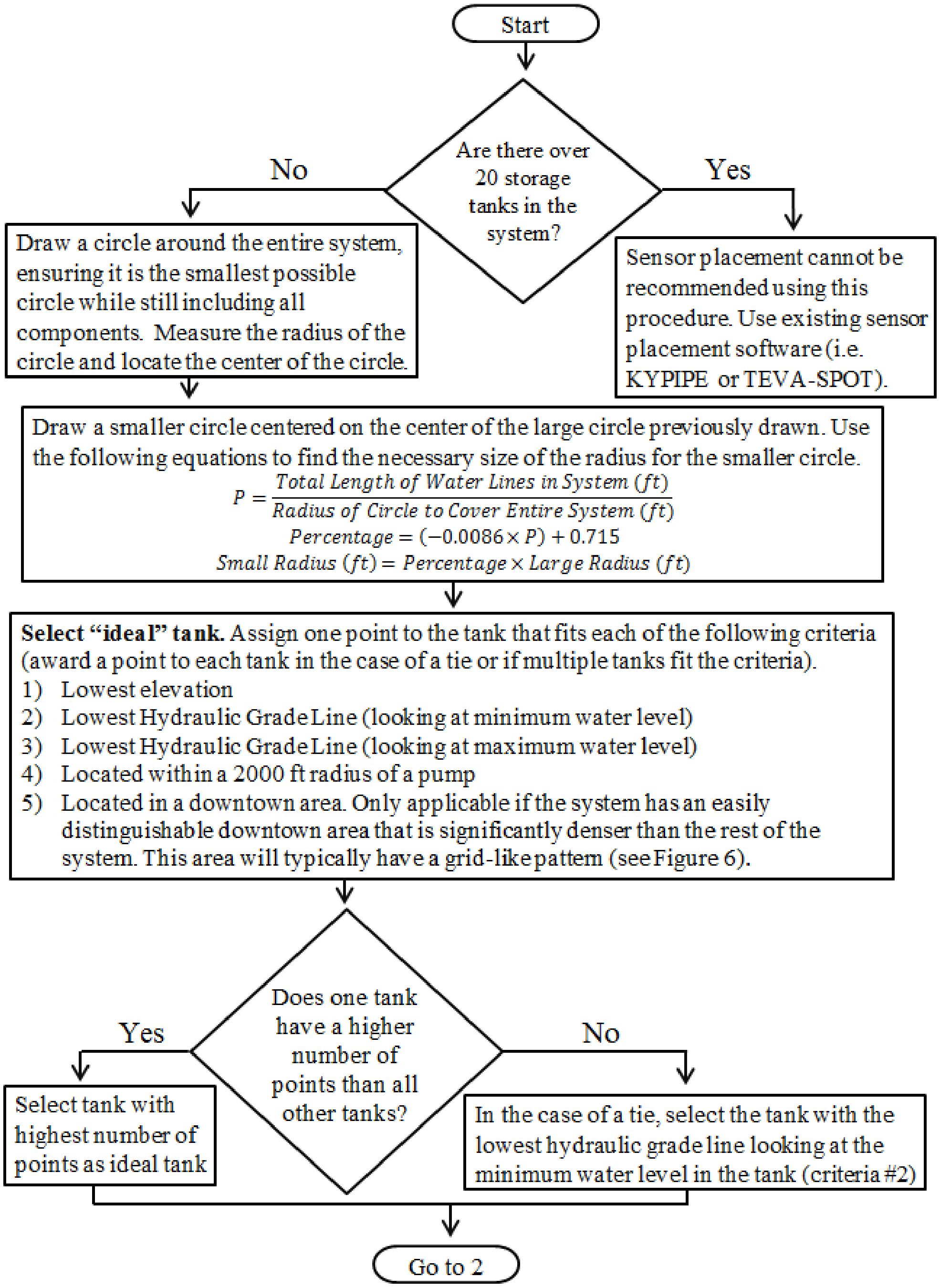

Figure 5. Ideal Tank Selection (Branch Systems)

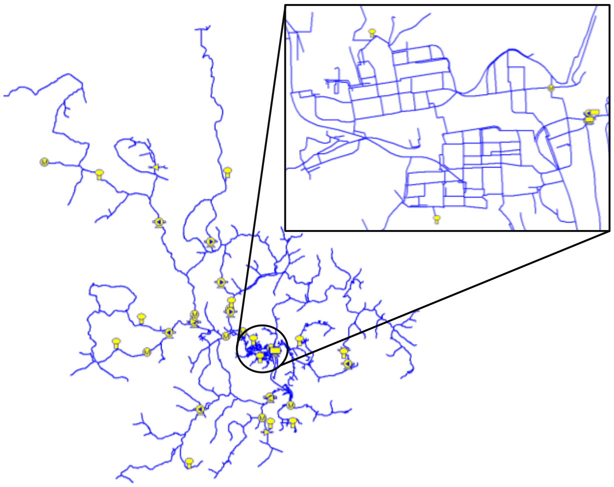

Figure 6. Example of Downtown Area (Branch Systems).

Draw a Circle Around the Ideal Tank

The third main step of the procedure is to draw a circle with a specified radius around the ideal tank. The loop and grid systems use identical equations and system parameters to determine the radius, and the branch systems follow a different equation utilizing different system parameters. A circle is drawn around the ideal tank using the calculated radius, with the tank as the center point of the circle. In this study, the buffer tool in the Geographic Information Systems (GIS) software was used to execute this step. However, a scaled map, ruler, and compass can be used to carry out this process by hand. For loop and grid systems, the total length of water lines in the system (in feet) along with the approximate area the system covers (in square miles) is needed. Note that this area is not found by drawing a circle around the network. The third step in the procedure for loop and grid systems is shown in Figure 7.

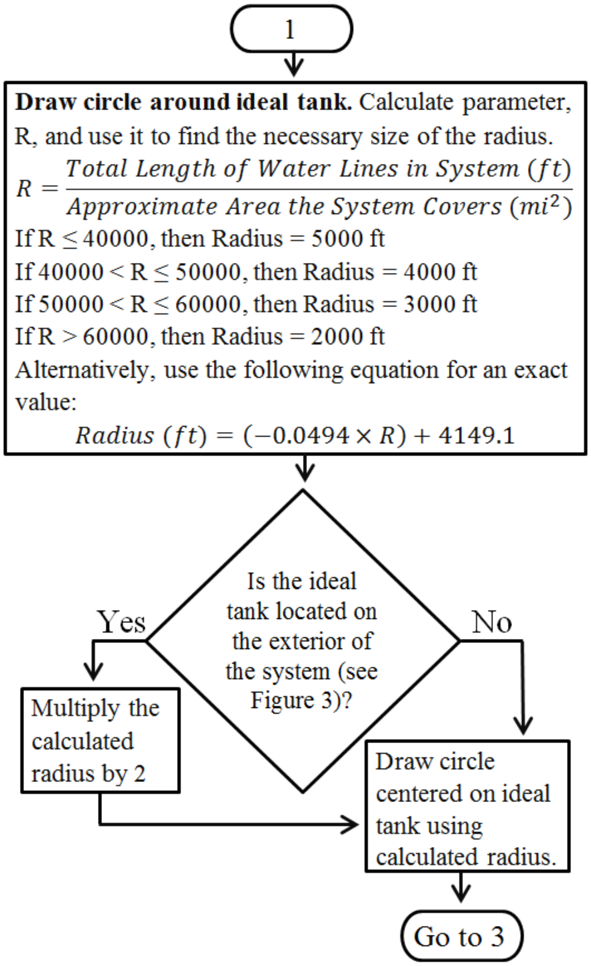

Figure 7. Circle Around Ideal Tank (Loop and Grid Systems)

For branch systems, the area of the large circle drawn to encompass the entire system in the ideal tank selection step is needed to create the circle around the ideal tank. This step is shown in Figure 8.

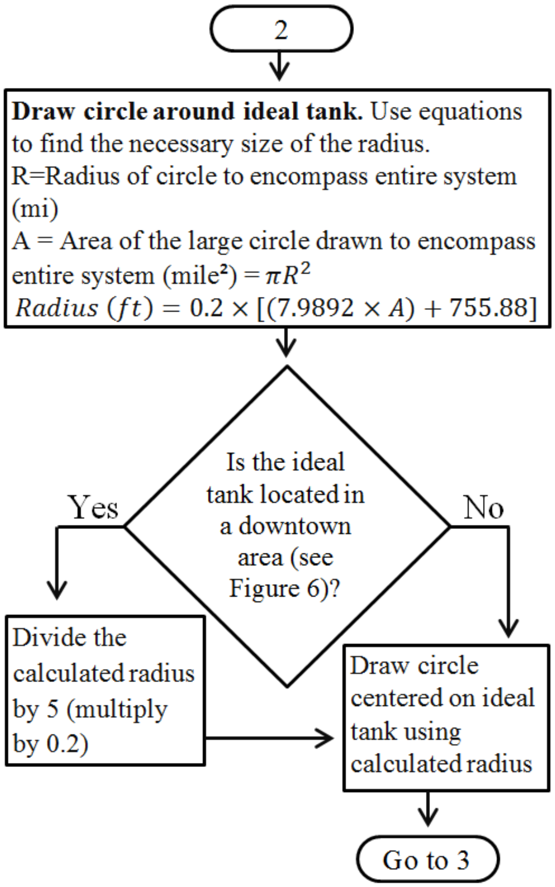

Figure 8. Circle Around ideal Tank (Branch)

Define Nodes, Collect Data, and Rank Nodes

The final three steps in the sensor placement guidance procedure are identical for all three system configurations. These steps include defining all nodes located within the circle, collecting data for these nodes, and ranking the nodes in terms of effectiveness as a sensor location. The final three steps in the procedure for all systems are shown in Figure 9.

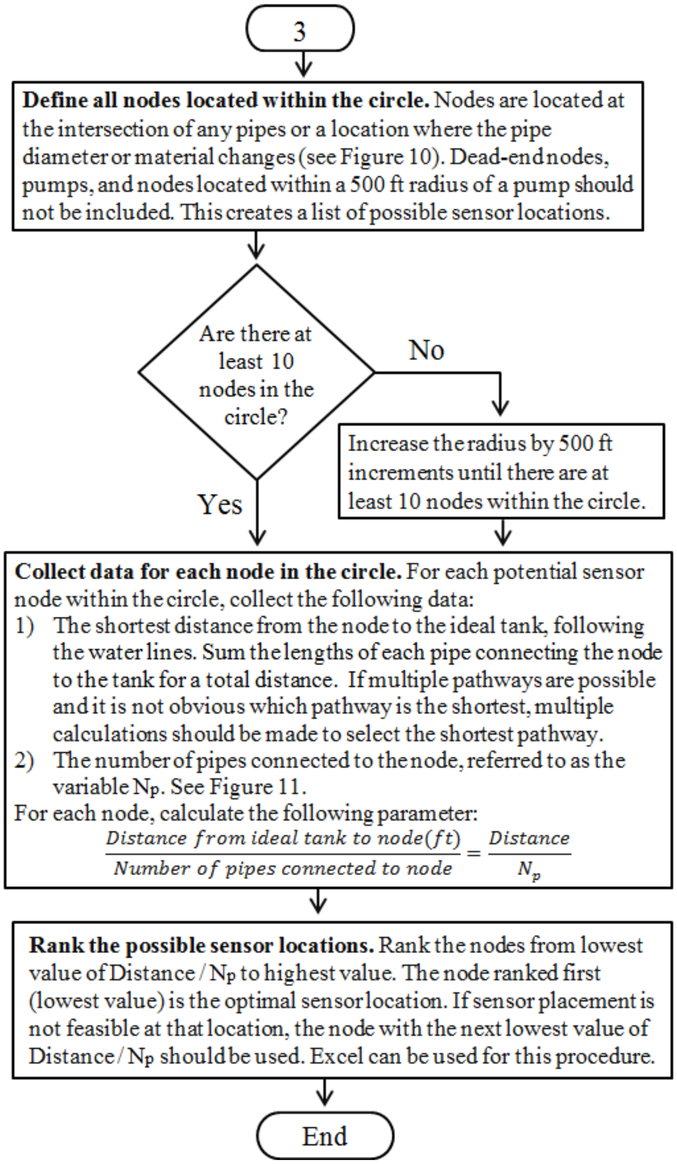

Figure 9. Final Steps (All Systems).

Figure 10 shows examples of portions of a system where the location of a node is appropriate, and this can be used as an aid when the user is defining nodes located in the circle.

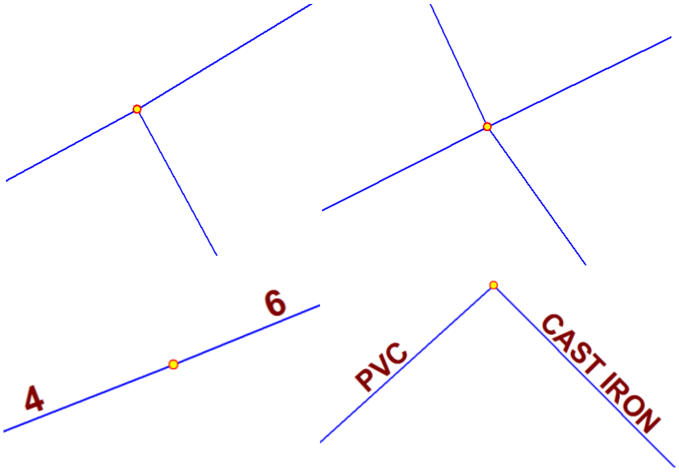

Figure 10. Examples of Nodes.

Figure 11 displays examples of various arrangements of pipes and the appropriate values for the variable N_p. The minimum possible value for N_p will be two because dead-end nodes should not be included as possible sensor nodes.

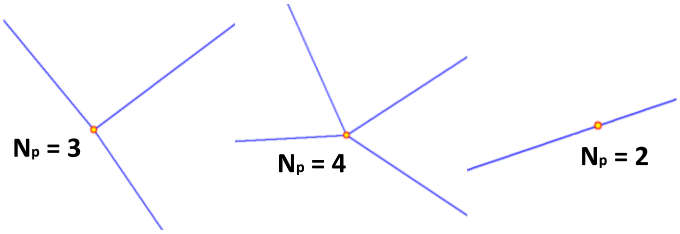

Figure 11. Examples of the Variable N_p.

After the nodes within the circle are ranked, the node with the lowest value of Distance/ N_p that is accessible and appropriate for placement of a sensor is considered the optimal sensor location. The purpose of the node rankings is to provide the user with a list of possible sensor locations ranked in terms of their effectiveness as a sensor location. It is unlikely that this method will rank the nodes in the exact order of effectiveness (measured by time to detection), but the general trend will be present. The utility manager will select the highest ranked node on the list that is suitable for sensor placement, theoretically choosing the most optimal node that is appropriate for a sensor.

The validity of using such an approach is illustrated for system KY 3 as shown in Figure 12. As the parameter Distance/ N_p (which can be developed for each node in the system) increases, the time to detection also increases. This general trend was present for nodes located within the circle of influence drawn around the ideal tank for all 12 systems. The point labeled as the gray circle in Figure 12 is considered the optimal location.

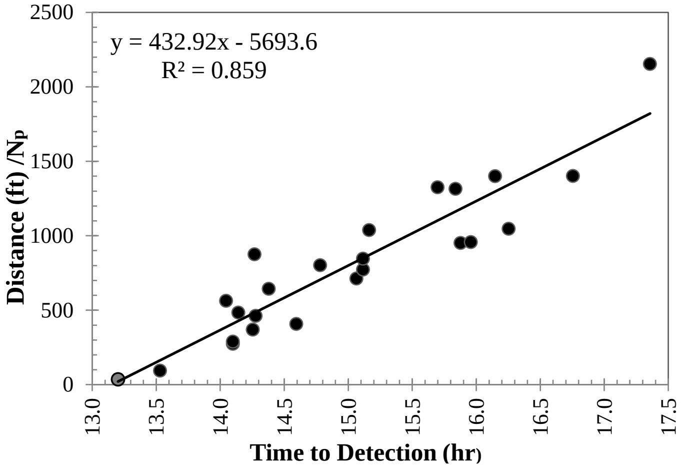

Figure 12. Distance/ N_p vs. Time to Detection for System Nodes (KY 3)

Verification of Sensor Placement Guidance

The procedure for placement of water quality sensors was developed using data from 12 water distribution system models (KY 1- KY 12). These models included four systems in each of the major system configurations: loop, grid, and branch. In order to verify the effectiveness of the sensor placement guidance, it was necessary to execute the procedure on distribution systems models that were not used in the development of the procedure. Three additional models (i.e. KY 13, KY 14, and KY 15) representing a grid, loop, and branch system, were used for this purpose. The KYPIPE sensor placement tool was also executed on these three systems, and the results from the proposed simple method and the KYPIPE algorithm were then compared to verify the effectiveness of the sensor placement guidance developed in this study.

It should be noted that 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 (only junctions that are not dead-end nodes). Therefore, the values reported for the number of possible sensor nodes, along with rankings and average times to detection, will only reflect possible locations in the guidance procedure.

The ideal node selected using the method developed in this study was compared to the sensor location chosen by the KYPIPE sensor placement tool for the three verification systems. Table 1 shows the nodes selected by both methods and their respective times to detection, the ranking of the node selected by the guidance procedure (based off times to detection provided by KYPIPE), and the differences in time to detection between the two methods.

Table 1. Comparison of Sensor Selection between KYPIPE and Procedure.

System	Possible Sensor Nodes	KYPIPE		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%

The verification of the sensor placement guidance developed in this study showed that the procedure performed favorably. In the verification of the procedure for grid configured systems (using KY 13), the KYPIPE sensor placement tool and the guidance developed in this study selected the same node, J-516, as the optimal sensor location. Therefore, the grid system was able to select the most ideal node using the guidance procedure.

The procedure tested on the loop system selected a node in very close proximity to the ideal node with a similar time to detection. For KY 14, KYPIPE selected J-221 and the guidance procedure selected J-136. J-136 was ranked third out of the 277 possible nodes for sensor locations based on the average times to detection produced by KYPIPE. The percent difference in average time to detection between the optimal node (selected by KYPIPE) and the node chosen by the guidance procedure is 2.4% (0.39 hours). Figure 13 shows that the two nodes are located in very close proximity to each other. It should also be noted that the ideal sensor chosen by KYPIPE (J-221) was ranked as the second best location by the guidance procedure. Therefore, the guidance developed in this study did an excellent job of selecting sensor locations for the loop systems.

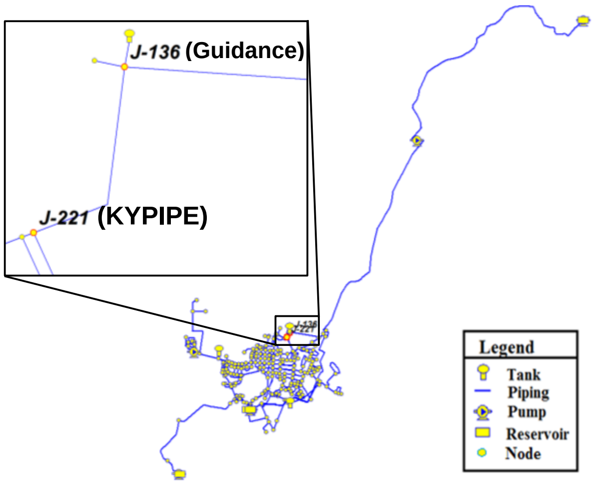

Figure 13. Sensor Locations Comparison (KY 14).

KY 15 was used to verify the effectiveness of the procedure developed for branch configured systems. The sensor placement tool in KYPIPE selected J-197 as the best location for a water quality sensor, and the guidance procedure chose J-476 as the ideal sensor location. The node chosen by the procedure was ranked 31st out of a possible 399 nodes, based on the times to detection provided by KYPIPE. The fastest time to detection was 17.15 hours, while the time to detection for J-476 was 17.72 hours. The difference in the times to detection was only 3.3% (0.57 hours). The spatial variation in the location of the two nodes can be seen in Figure 14.

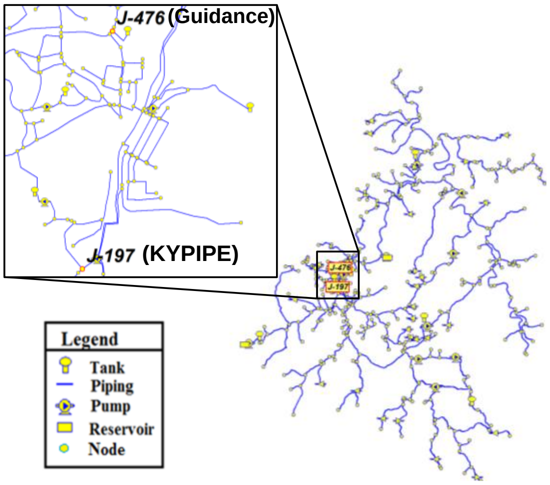

Figure 14. **Sensor Locations Comparison (KY 15).**

When looking at the entirety of the system in Figure 14, the two nodes seem to be located fairly close to each other. When the zoomed portion of the figure is observed, it becomes obvious why the guidance procedure did not select the best node. During the tank selection step, T-4 (located directly next to J-476) was selected as the ideal tank. When average times to detection provided by KYPIPE were examined, it was apparent that the nodes with the fastest times to detection were located around T-6 (located slightly northwest of J-197). Therefore, even though the procedure did not select what is considered the most ideal tank surrounded by the nodes with the fastest time to detection, it did select a tank in close proximity that was surrounded by nodes with times to detection that were very close to the fastest time.

Branch systems typically have a greater number of storage tanks than the loop or grid systems, making it slightly more difficult to select the ideal tank that is surrounded by the nodes with the lowest times to detection. This is a slight limitation of the guidance procedure when using it for a branch configured system. However, the verification process utilizing the KY 15 system showed that even if the best tank is not chosen in the tank selection process, the procedure will still be able to select a tank that is near nodes with relatively fast times to detection. Overall, the guidance procedure for the placement of one sensor behaved well compared to the KYPIPE sensor placement tool.

Summary and Conclusions

Software has been developed to aid utilities in identifying the optimal placement for water quality sensors. Many of these methods use information about flow dynamics in a system, which requires using calibrated hydraulic and water quality models. However, small utilities typically do not have the financial resources or expertise to build the models necessary to utilize the software. Because of such limitations, a simple procedure was developed for use in recommending the optimal placement of a single water quality sensor without the use of a hydraulic model or complicated algorithm.

The developed procedure does not require any information about flow dynamics and instead utilizes simple information about the geometry of the system. Although the simplified method may not be as reliable as current sensor placement software (e.g. TEVA-SPOT or KYPIPE), it should provide an effective solution for small utilities with limited resources. The sensor placement guidance procedure, unique to each of the three system configurations, was tested on three system models that were not used in the development of the procedure. The procedure performed favorably, demonstrating the method should be effective in recommending sensor placement that maximizes the ability to detect contamination events. This procedure can serve as a tool for managers of small utilities to determine the optimal placement of one water quality sensor using minimal time and resources. Future research in this area will expand the number of water quality sensors, to provide guidance to utilities with resources to deploy more than one water quality sensor.

Acknowledgement

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