2013

WATER QUALITY SENSOR PLACEMENT GUIDANCE FOR SMALL WATER DISTRIBUTION SYSTEMS

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WATER QUALITY SENSOR PLACEMENT GUIDANCE FOR SMALL WATER DISTRIBUTION SYSTEMS

THESIS

A thesis submitted in partial fulfillment of the
Requirements for the degree of Master of Science in Civil Engineering
in the College of Engineering
at the University of Kentucky

By

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Lexington, KY

Director: Dr. L. Sebastian Bryson, Associate Professor of Civil Engineering

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2013

ABSTRACT OF THESIS

WATER QUALITY SENSOR PLACEMENT GUIDANCE
FOR SMALL WATER DISTRIBUTION SYSTEMS

Water distribution systems are vulnerable to intentional, along with accidental, contamination of the water supply. Contamination warning systems (CWS) are strategies to lessen the effects of contamination by delivering early indication of an event. Online quality monitoring, a network of sensors that can assess water quality and alert an operator of contamination, is a critical component of CWS, but utilities are faced with the decision of what locations are optimal for deployment of sensors. A sensor placement algorithm was developed and implemented in a commercial network distribution model (i.e. KYPIPE) to aid small utilities in sensor placement. The developed sensor placement tool was then validated using 12 small distribution system models and multiple contamination scenarios for the placement of one and two sensors.

This thesis also addresses the issue that many sensor placement algorithms require calibrated hydraulic/water quality models, but small utilities do not always 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.

KEYWORDS: Water Quality Monitoring, Contamination Warning Systems, Water Security Monitoring, Sensor Placement Guidance, Model Database.

Stacey L. Schal

December 4, 2013

WATER QUALITY SENSOR PLACEMENT GUIDANCE
FOR SMALL WATER DISTRIBUTION SYSTEMS

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ACKNOWLEDGEMENTS

I would first like to acknowledge my advisor Dr. L. Sebastian Bryson. Dr. Bryson guided me through all stages of this research project and was committed to helping me achieve success with both my research and overall academics. I would also like to acknowledge Dr. Lindell Ormsbee, who played a crucial role in the success of my research and offered expertise during many stages of the project. Dr. Srini Lingireddy also played an essential role with his tireless efforts developing sensor placement guidance in the KYPIPE software and also offering general guidance working with the program throughout the course of the project.

I would also like to thank my professors at the University of Kentucky, who allowed me to expand my knowledge and ability to learn in the classroom: Dr. Scott Yost, Dr. Lindell Ormsbee, Dr. Michael Kalinski, Dr. Y.T Wang, Dr. Alan Fryar, along with other professors at UK who guided me through my undergraduate career as well. I would also like to thank both Dr. Scott Yost and Dr. Jimmy Fox for encouraging me to pursue the water resources field through my interest in their courses and research experiences. I am very grateful for the education I have received at UK, and I appreciate the efforts by my professors in helping me earn my education.

I want to thanks others who provided guidance and assistance during the course of this research. I would like to thank Bill Gilbert, Joe Goodin, Matthew Jolly, and Steven Hoagland for their contributions to this research.

Most importantly, I want to thank my family and close friends for their support in this journey. My parents, Rick and Ginger Schal, provided constant support, without which I would not have been able to accomplish so much. They have always supported my dreams throughout life, and I am blessed to have such a strong support system. I also thank Wesley and Evan Loxley for their encouragement and for serving as exceptional role models. I especially thank my sister, Wesley, for encouraging me to pursue engineering and continuing to push me along the way. My persistent efforts throughout our lives to achieve close to what she has accomplished taught me the value of hard work and determination. I also thank Brandon Isaac for his constant support and encouragement, for always pushing me to reach my goals and never allowing me to give up. I also thank him for pushing me to achieve excellence through healthy competition. I believe that a little bit of his exceptional work ethic and desire to learn rubbed off on me, and I am a much better student and person because of it.

Funding for this research was provided by the U.S. Department of Homeland Security, Science and Technology Directorate, through a technology development and deployment program managed by The National Institute for Hometown Security, under an Other Transactions Agreement, OTA #HSHQDC-07-3-00005, Subcontract #02-10-UK. This support was greatly appreciated.

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CHAPTER 1

1 Introduction

1.1 Background

Water distribution systems are an integral part of society, and the availability of a clean and dependable supply of water influences both the socioeconomic status and health of a populace. In recent years, protecting the nation's critical infrastructure from terrorist attacks has become a priority, and efforts to protect the water infrastructure are included in this goal. 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, greatly increasing the risk and potential danger associated with an attack (Hart & Murray, 2010).

Public awareness of this threat has also increased from media coverage of two international terrorist plots against drinking water systems. One attack planned to introduce a cyanide compound into water lines near a U.S. Embassy in Italy, and another was a direct threat from an Al-Qaeda operative to American water supplies (Murray et al., 2010). Threats to the nation's water supply are concerning because they can cause a significant negative impact to public health and the economy in a short amount of time. Possible terrorist attacks to water supplies include sabotage of Supervisory Control and Data Acquisition (SCADA) systems, the physical destruction of facilities, airborne release of hazardous chemicals onsite, and the injection of chemical, biological, or radiological contaminants into the water supply. The threat of contaminant injection is perhaps the most dangerous because of the major public health, economic, and psychological impacts that could result (Murray et al., 2010).

Intentional contamination of water distribution systems has become an increasing concern in recent years, but the accidental contamination of drinking water is also possible. Humans can unintentionally contaminate distribution systems with pesticides, toxic industrial chemicals, or other materials. Systems can also be contaminated if metals, organic contaminants, or asbestos in pipe materials and linings are able to leach into the network. The risk of soil and groundwater contaminants permeating through plastic pipes is also present. Pesticides, insecticides, or other chemicals are able to enter the system through accidental backflow occurrences or breaks in pipes/leaky joints (Murray et al., 2010). In an effort to mitigate the risks from intentional or accidental contamination of the water supply, contamination warning systems have been proposed as a cost-effective and reliable strategy.

Contamination warning systems (CWS) are proactive strategies to lessen the effects of a contamination event in a water distribution system. The goal of a CWS is to deliver an early indication of intentional or accidental contamination in order to reduce public health impacts and economic loss, and it also works to improve the water utility's capability for a quick response (Janke et al., 2006). A CWS includes deployment and operation of online sensors, other surveillance systems, fast communication technology, and data analysis procedures to provide early alert of a contamination event (Murray et al., 2010). Arguably the most critical component of CWS, classified as online quality monitoring, involves the network of sensors that can assess the quality of water in the distribution system and alert an operator of a potential contamination event. Utilities developing these water quality monitoring systems are faced with the decision of what locations are best suited for deployment of these sensors; the location of these sensors is a critical component of a CWS. These water quality sensors must be placed in locations that maximize their ability to detect contamination events and provide the greatest protection of human health (McKenna et al., 2006).

1.2 Research Tasks Description

To date, there is no applicable federal or state guidance to assist utilities in the deployment of water quality sensors. Distribution systems are complex, dynamic infrastructures that differ greatly for individual utilities. This creates difficulties in the development of general guidance for sensor placement that are applicable to all distribution systems. Technological advancements in sensor placement optimization software may help solve the problem of sensor placement issues for some utilities.

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 model is setup in EPANET (U.S. EPA, 2008), and this is used as input for

TEVA-SPOT (Berry et al., 2010) to recommend sensor placement based on a variety of user defined objectives. However, this software does not have the ease of use and simplicity that is needed to be beneficial to small utilities. It requires the use of complex water quality models along with sophisticated optimization methods to perform sensor placement guidance. Many small, or even medium sized, utilities might not have the technical or financial resources that are needed to effectively use TEVA-SPOT. Because of deficiencies in the current resources, the first phase of this research is aimed at developing a sensor placement algorithm in the KYPIPE program as a simple tool to aid small utilities in sensor placement.

The KYPIPE software is already useful in allowing utility managers to gain a better understanding of the flow dynamics and overall behavior of their distribution system. The Water Quality (WQ) sensor placement tool can be used within the KYPIPE program to offer helpful information and recommendations for water quality sensor placement. The tool will recommend optimal locations for online sensors based on simple water quality analyses and heuristic methods that require very little or no added input from utilities. The goal is to provide a simple tool to aid utility managers in the optimal placement of sensors within their distribution systems in order to minimize the negative events of a contamination event.

The newly developed sensor placement tool is tested on a database of twelve distribution system models that are considered small utilities. The tool is executed with a variety of contamination scenarios for all systems, placing a number of sensors reasonable for the budget of a small utility. The same scenarios are also executed using the TEVA-SPOT software, both programs operating with the objective of minimizing the time required to detect the contaminant based on the given contaminations scenario. The results from both programs for all executions are compared in order to verify the effectiveness of the new KYPIPE sensor placement tool.

Although the new sensor placement algorithm acts as an effective tool in sensor placement, use of this algorithm still requires a hydraulic/water quality model of the network. Model creation can be costly and time consuming, and many small utilities may 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 these issues that may prevent small utilities from being able to utilize the newly developed sensor placement algorithm, it was desired to develop a procedure to recommend sensor placement without the use of a model or complicated algorithm. Small utilities would not have to invest significant time and resources building calibrated models of their systems in order to utilize sensor placement guidance. As a result, the second phase of this research aims to develop a sensor placement guidance procedure for the placement of one sensor that did not require a hydraulic/water quality model of the system.

In order to develop the sensor placement procedure, the recommended sensor locations from the KYPIPE sensor placement tool were analyzed to determine if patterns exist based on system characteristics and system configuration. Trends in the optimal sensor locations were observed based on certain system parameters, resulting in the development of a procedure that varied by system configuration. 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 currently available sensor placement software, it should provide an effective solution for small utilities with limited financial and technical resources.

1.3 Objectives of Research

The objectives of this research are as follows:

1) Develop and test a sensor placement algorithm in the KYPIPE program

- Develop sensor placement tool in KYPIPE as a simple tool to aid small utilities in sensor placement
- Execute new KYPIPE sensor placement tool on model database of 12 small water distribution systems for a variety of contamination scenarios
- Use TEVA-SPOT to run sensor placement simulations on the same models and contamination scenarios
- Compare results given by KYPIPE and TEVA-SPOT to verify the effectiveness of the new sensor placement tool

2) Develop a simplified procedure to recommend sensor placement without the use of a model or complicated algorithm

- Develop a sensor placement guidance procedure for the placement of one sensor that does not require a calibrated hydraulic/water quality model of the system
- Execute developed procedure on three additional models created strictly for verification purposes
- Use sensor placement algorithm in KYPIPE to determine optimal sensor placement in the three additional verification models
- Compare results from both methods to verify the effectiveness of the developed sensor placement guidance procedure

1.4 Contents of Thesis

Chapter 2 presents a technical background on topics to support the contents of this research. This includes information about the development of water distribution system models and a statistical study relating various system parameters to the general system configuration. Chapter 3 presents the sensor placement algorithm developed in the KYPIPE software to provide sensor placement guidance to small utilities. This chapter outlines the methodology of the algorithm and also includes a verification study comparing results to that of the TEVA-SPOT software. Chapter 4 presents the simplified sensor placement guidance procedure developed to aid small utilities in the placement of one sensor without the need for a model of their system. Chapter 5 presents the alternative, graphical sensor placement guidance procedure that will also aid small utilities in the placement of one water quality sensor without a calibrated model or complicated algorithm. Both Chapter 4 and Chapter 5 contain verification studies for the developed sensor placement guidance procedures. Chapter 6 contains conclusions of this research.

Appendix A presents additional data and information used in the statistical testing of systems in the model database. Appendix B presents the developed sensor placement guidance procedures, including both the simplified full procedure and the graphical procedure. Both methods are outlined and also presented in flowcharts. This appendix also contains an example of the procedures executed on a distribution system in each of the general system configurations. Appendix C presents the execution of the sensor placement guidance procedures on the three additional verification systems. Appendix D outlines the development of the sensor placement guidance procedures and includes data for each of the twelve systems used in the development process. Appendix E contains results for all simulations with the KYPIPE sensor placement tool and the TEVA-SPOT software. Additional resources relating to this research are included in a previous report (University of Kentucky and KYPIPE LLC, 2013). This includes a full literature review, procedure to create models of distribution systems, procedure to execute the sensor placement tool in KYPIPE, and the layout of every system model used in this study. It should be noted that the report contains preliminary results, and more recent results are contained herein.

CHAPTER 2

2 Statistical Characteristics of Water Distribution Networks

2.1 Introduction

Water distribution systems are responsible for providing a clean and reliable source of drinking water to communities. System models are typically developed by utilities to perform long-term planning, design new components, and resolve hydraulic or water quality problems (Murray et al., 2008). A simple analysis of pressures and flows in a network over time can be helpful in providing information to a utility about the behavior and characteristics of their distribution system. Models are also utilized by researchers in developing new methodologies and algorithms to aid in planning, design, and operation of systems. This research can range from achieving reliability and optimal operation of a system to water security issues like ideal placement of water quality sensors.

This paper discusses the process used to create a hydraulic network model using standard GIS datasets (e.g. shapefiles and attribute tables). The presented methodology is illustrated using a well-known network analysis model (i.e. KYPIPE), but the general methodology will be applicable for most other commercially available software as well (e.g. Innovyze, WaterGEMS, etc.). In this case, 15 separate models were generated using an online GIS database of water utilities in the state of Kentucky. The resulting database is then used to evaluate differences in system characteristics associated with three different classes of system configurations: grid, loop, or branch systems.

This study aims to further investigate the systems to help quantify differences in the system configurations beyond the general layout differences. All 15 models used in this study can be characterized as one of the three main system configurations, and the models were selected based on their spatial configuration and also their diversity in general system characteristics such as number of pumps, tanks, and reservoirs. Differences in basic system characteristics based on configuration will be investigated to determine if characteristics such as the number of tanks or average pipe diameter vary systematically by configuration. If trends are present in certain parameters for systems categorized as the same configuration, this information can be useful for several applications. The most basic application would be to use these parameters as tools for classifying systems accurately into the correct configuration.

2.2 System Configurations

Each model discussed in this paper can be classified as one of the three basic system configurations for water distribution networks: branch, loop, or grid. Figure 2.1 shows a diagram displaying the basic setup of each system configuration.

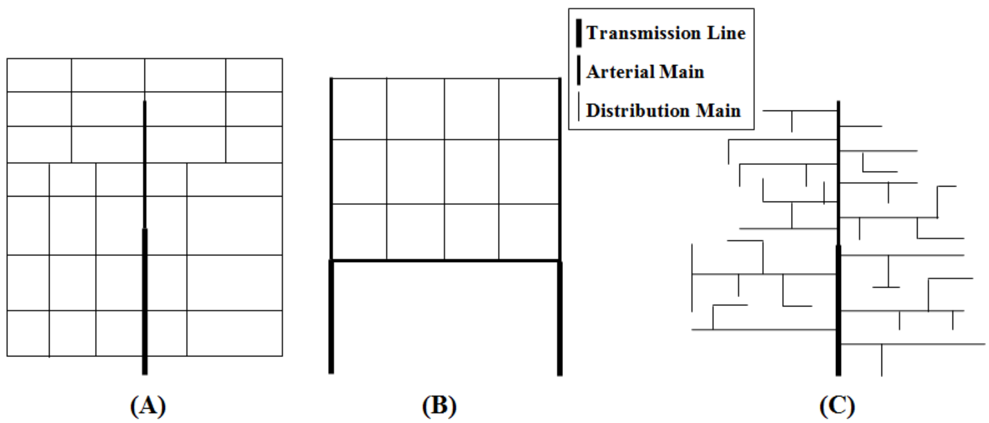


Figure 2.1: Water Distribution System Configurations (taken Von Huben, 2005): (A) Loop; (B) Grid; (C) Branch.

2.2.1 Branch Configuration

A branch system is named for its similarities to a tree branch. Smaller pipes branch off more centralized, larger pipes so that water can theoretically only take one path from the source to customers (National Research Council, 2006). This type of system is frequently used in rural areas where the service area is fairly large, but some consumers in the far branches are spaced far apart from each other. High flows are experienced in the large transmission lines running through the center of the system, and lower flows are present in distribution mains as pipes become smaller farther away from the center of the system. These systems contained more pumps, tanks, and a greater total length of water lines because the systems are more spread out. Even though these systems typically contain a greater total length of pipeline than other configurations, the average diameter of pipes are usually smaller. An example of a system in branch configuration is shown in Figure 2.2.

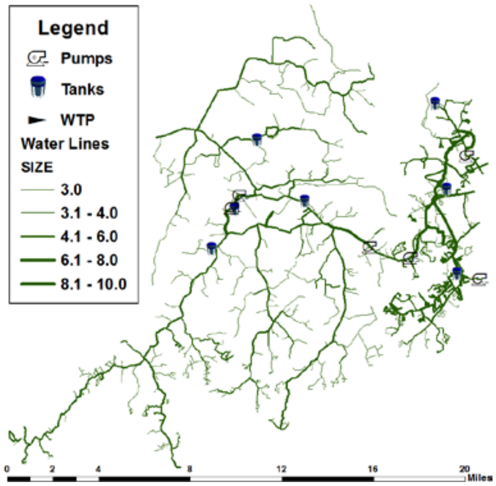


Figure 2.2: Branch Configuration.

2.2.2 Loop Configuration

The branch system is typically easy to distinguish, but the loop and grid systems have similar characteristics and it is sometimes difficult to classify systems into these configurations. Both systems consist of connected loops of pipelines, allowing several pathways that the water can flow from the source to customers. These system configurations are more widely used in large municipal areas or densely populated systems (U.S. Environmental Protection Agency, 2008). Loop and grid systems are considered very reliable because line breaks can be more easily isolated, allowing only a small portion of the system to be affected (National Research Council, 2006). Looping is not only advantageous because it provides continuous service even if a portion of the system is shut down, but it also provides flow from multiple directions for reliable fire flow and reduces the number of dead-ends that potentially cause water quality problems (McGhee, 1991).

In loop systems, there is typically a large, centralized transmission line that feeds smaller lines. The purpose of the central lines is to supply high flows from the source through the middle of the system, and the system then transitions to lower flows as the lines move outward from the central area. These smaller lines connect at each end into the main loop (Von Huben, 2005). An example of an actual distribution system classified as having a loop configuration is shown in Figure 2.3.

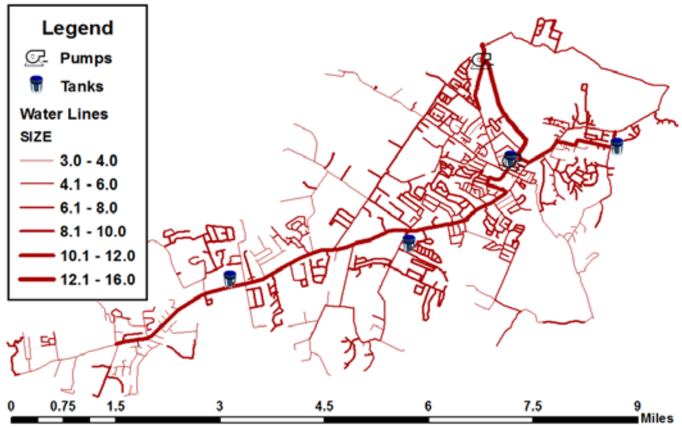


Figure 2.3: Loop Configuration.

2.2.3 Grid Configuration

In grid configured systems, the water lines are laid out to look similar to a checkerboard. The main water line infrastructure, consisting of the larger pipes in the system, 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). An example of a distribution system in grid configuration is shown in Figure 2.4.

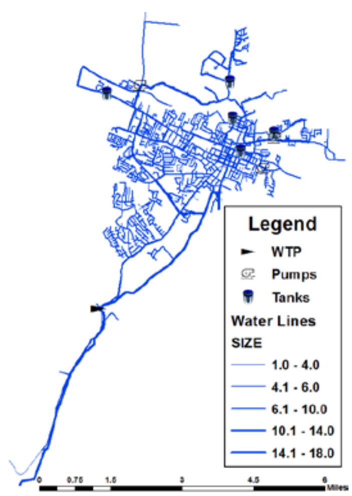


Figure 2.4: Grid Configuration.

Many systems are a combination of different configurations (systems containing both looped and branch configurations are common). However, for the purposes of this paper, all systems were classified strictly as one configuration based on which configuration characteristics were most prominent.

2.3 Development of Water Distribution System Models

The model database used in this study consists of 15 network models, all representing real distribution systems located in Kentucky. Each of the models was constructed using data obtained from the Kentucky Water Resources Information System (WRIS) which is supported by the Kentucky Infrastructure Authority (KIA). This system contains GIS shapefiles and attribute tables for various system components for each system in the database. In developing the database, the shapefiles for water lines, pumps, tanks, and water treatment plants were downloaded and imported to ArcGIS (Geographic Information Systems) before subsequent processing in the KYPIPE model graphical user interface.

The shapefiles acquired from the KIA database do not have elevation data associated with them. Therefore, digital elevation models (DEM) were necessary to assign elevations to system components. This data was acquired from the National Resources Conservation Service (United States Department of Agriculture). Once shapefiles and attribute tables containing system components and elevation data was acquired, a series of imports and exports of data between GIS and KYPIPE was executed to create a working hydraulic model. The general process of model creation is outlined in Figure 2.5.

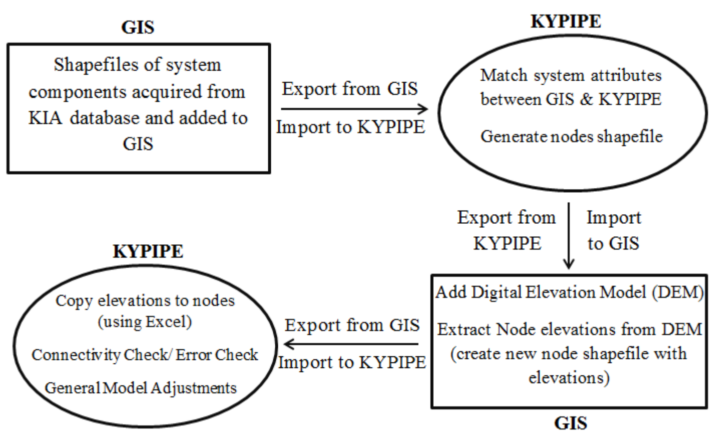


Figure 2.5: Model Creation Procedure.

2.3.1 Procedure for Model Creation

The model database used in this study was created by following a procedure that utilized the ArcGIS software package. The data for all necessary distribution system components (water lines, pumps, tanks, and water treatment plants) was first downloaded from the Water Resources Information System and added to a blank ArcGIS document (Kentucky Infrastructure Authority, 2010). The files for meters, surface sources, well sources, and purchase sources were also available, but these components were not necessary for the purpose of this study. In the process of model creation, only the data for the specific utility of concern is necessary. A clause was formulated to isolate parts of the shapefiles based on the “owner” attribute, and this action selected all the data associated with the specific utility from data for the entire state. Shapefiles of all system components were then exported from ArcGIS.

The data exported from GIS needed to be input to KYPIPE. The option to import an ArcView file was selected in KYPIPE, and the Shape File Import Utility was first used to import the water lines shapefile. The utility displayed a list of fields in KYPIPE along with attributes present in the shapefile from GIS. Characteristics of each system component were transferred from the attribute table in GIS to the KYPIPE file by selecting an attribute in KYPIPE and matching it with the corresponding attribute in GIS. Attributes were matched for tanks, pumps, and reservoirs, similar to the process for pipes, and the data was processed for each system component.

Completion of the procedure thus far resulted in a KYPIPE model containing all of the necessary system components: pipes, tanks, pumps, and reservoirs. All components contained accurate (X,Y) coordinates, but the model did not contain elevation data associated with system components. Therefore, it was necessary to acquire elevation data for the area encompassing the utility and assign values of elevation to components in the model. A Digital Elevation Model (DEM) was acquired from the National Resources Conservation Service Geospatial Data Gateway (United States Department of Agriculture). The site presented a list of National Elevation Datasets grouped by county and various grid cell sizes. A 10 meter DEM will consist of 10m x 10m grid cells with a corresponding value for elevation, so the smaller grid cells result in more accurate elevation data.

A shapefile of all nodes in the KYPIPE model was first generated to add to GIS and later combine with the DEM. The option to export an ArcView file was selected in KYPIPE, and the utility was set to export nodes along with their name attribute to create a shapefile named "Nodes". This shapefile was added to the ArcMap document, and the components of the nodes shapefile visually lined up with the water lines layer. Each utility will typically require multiple DEM files, so multiple elevation files were added to the ArcMap document until all of the nodes in the system were covered by a DEM. It was then necessary to combine all DEM files using the "Mosaic to New Raster" tool in ArcGIS. Figure 2.6 displays a system showing the DEM along with the nodes shapefile that lined up with the water lines.

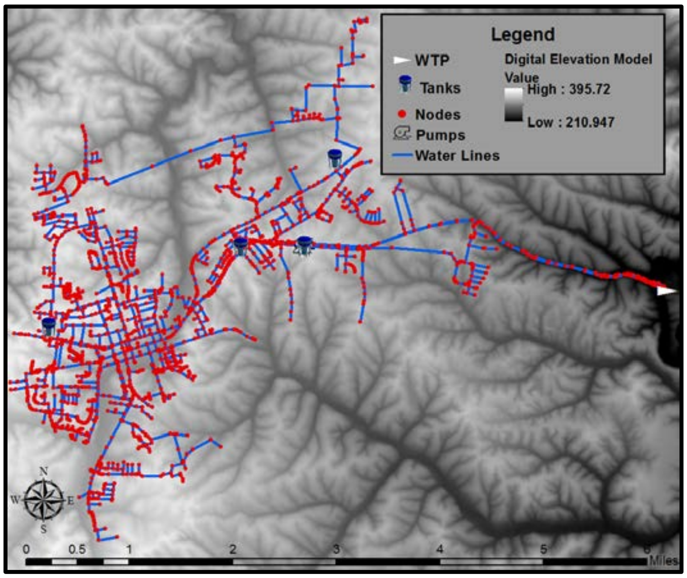


Figure 2.6: Digital Elevation Model.

Once the individual DEMs were combined into one, the next step was to extract the elevation data to each node using the "Extract Value to Points" tool. The process created a new shapefile containing the nodes from KYPIPE with assigned elevations from the DEM. To add elevations to the KYPIPE model, the Nodes file (file extension .dbf) containing the node names with assigned elevations in meters was opened in Excel. The nodal elevations were converted to feet, and the data was copied to the Elevation column in the data table for nodes in the KYPIPE model.

Completion of the outlined steps resulted in a model containing all distribution system components with elevations assigned to each component and nodes throughout the system. However, other alterations were required to fix errors that could have occurred in the model creation process. Various tools in KYPIPE were utilized to help detect possible errors, and similar functionality exists in other commercial software as well. In KYPIPE, the "Connectivity Check" tool was used to highlight pipes that were not connected to the rest of the system. These pipes were then evaluated to see if they actually represented dead-end segments or if the shapefile simply did not contain the node to which they were actually connected. Such information can be verified from construction records/as-built drawings or from discussions with system operators. To fix pipes that were unintentionally disconnected from the system, the pipe was manually extended in the same direction to a node in a nearby pipe. If a node was not present nearby, an intermediate node was added to the nearby pipe and the elevation of this node was interpolated. In all cases, it was obvious where the pipe should extend and connect to the system. It was also true in most cases that the pipe appeared to be connected when observing the system at a normal zoom level, and the disconnection was only noticeable if the portion was zoomed in at high levels that the user would not typically use. Figure 2.7 illustrates this concept. The left portion (A) represents a normal zoom level where the disconnection is not noticeable, but the problem is obvious on the right portion (B) using a very high level of zoom.

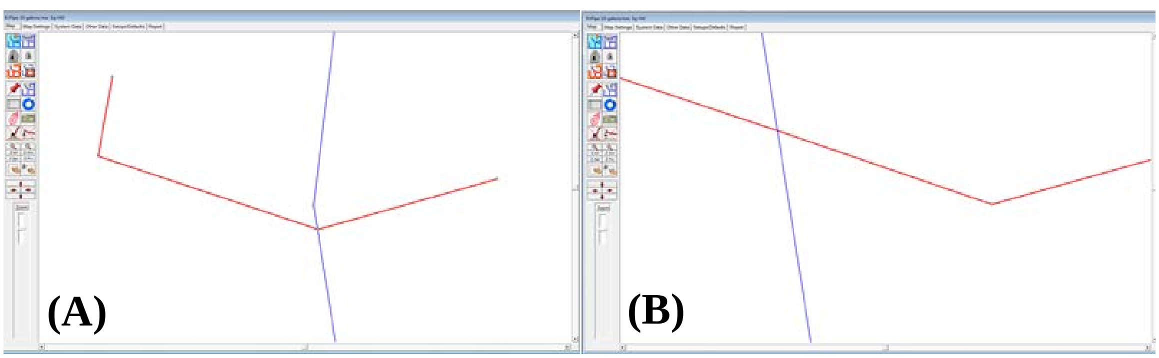


Figure 2.7: Example of Connection Errors: (A) Normal Zoom; (B) High Zoom.

In the case where the numerical model (e.g. KYPIPE) also has a water quality or water age determination feature, this type of analysis can also be used to identify situations where pipe segments may be disconnected from the system. Nodes that appear to correspond to a connection with another pipe when they are not actually connected would typically yield a much older water age or lower constituent concentration. Checking for such ages or concentrations can thus serve as a potential screening process for such connection errors.

After evaluating each model for possible connection errors, the “Error check” tool was then utilized in KYPIPE to check for other general errors, such as undefined initial elevations in tanks, an undefined grade in a reservoir, or an extremely high value for pump power.

2.3.2 Additional Adjustments to Models

Once the physical geometry of each network was confirmed, various components were added to the model to make the system more realistic to how a real system would behave in an extended period simulation (EPS). These components will only be briefly outlined because this study focuses on geometric elements of distribution systems.

Pipe roughness coefficients were assigned to each pipe in each model to account for head loss in the pipes due to friction. In a real world application, this would typically involve the assignment of Hazen-Williams roughness coefficients to each pipe based on pipe age and material and then further refinement through model calibration (Ormsbee and Ligireddy, 1997). For the current study, only non-calibrated models were developed. As a result, the estimates of pipe roughness were based on pipe material and age using a table of typical average C factors (AWWA, 2005). Pipes made out of smoother material, such as PVC, will have higher C coefficients than materials with greater roughness values like cast iron. Similarly, older pipes of the same material that have experienced significant corrosion and deposition will have lower coefficients than new pipes of the same material (Walski et al., 2003).

Water demand data was also incorporated into the model. The most accurate method of demand distribution would be acquiring meter data from the utility and applying this actual demand data to nodes throughout the system (AWWA, 2012). This process was not feasible for creating a database of 15 models, so an estimation of the demand allocation was used. Demand data was first acquired from the WRIS database for total water usage in million gallons per year for each system (Kentucky Infrastructure Authority, 2010). The Automatic Demand Distribution tool in KYPIPE was used to allocate the total demand to nodes throughout the system based on the diameters of adjacent pipes. It assigns greater values of demand to larger pipes, modeling higher flows in large pipes and lower flows in small pipes. This is fairly representative of how a real system operates, except for the case of large transmission lines. Transmission lines usually do not directly service a high amount of demand (Mays, 2000). However, this process does meet the goal of distributing the total average daily demand throughout the system in the general pattern that smaller pipes will service lower demands. This demand allocation process was deemed accurate enough for the purposes of this study.

Because water usage in a typical water distribution system has varying water demand patterns throughout the day, it was necessary to implement demand patterns over a 24 hour period. Implementing a demand pattern that applied to all parts of the system was deemed sufficient for this study. KYPIPE calculated nodal demand by multiplying the stated demand at each hour by a "demand factor" developed by the American Water Works Association (AWWA, 2012). The factors were less than one during the night when demand would be low and above one during the day when demand is the highest. The demand factors used in the study are shown in Figure 2.8.

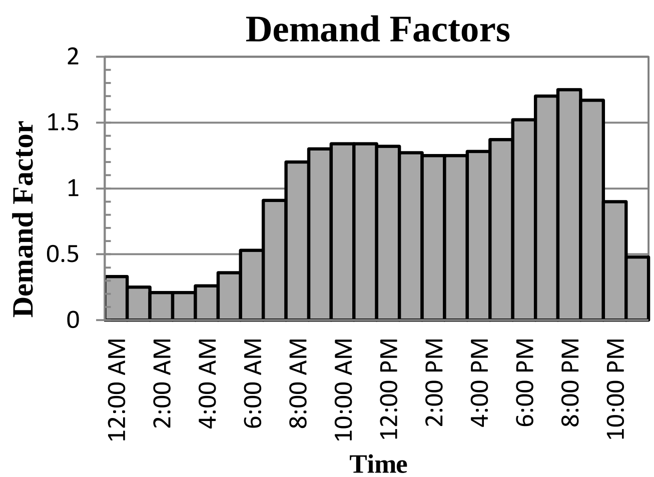


Figure 2.8: Demand Factors.

Various characteristics used to describe distribution systems in the model database were further modified to simulate the behavior of real systems. Changes were made to create models that operated under reasonable pressure ranges, and this was assumed to be between 40 and 150 psi. For example, problems with high pressures were typically solved by lowering tank levels, decreasing roughness values for pipes, decreasing the power of some pumps, and adding pressure regulators in some areas. In some cases of extreme high pressure, pumps were removed completely. This was deemed reasonable because some pumps were used to pump flows to nearby water districts which were not included in the main model of the distribution system. In such cases, the pump stations can be replaced with a single node representing the total demand of the water district. The fact that such changes had to be made to get most of the models to yield realistic flows and pressures underscores the importance of model calibration in real world applications.

As indicated previously, ideally a field calibration would be executed for each water distribution system to create models that accurately represent the actual system. Elevation data for all system components would be verified with surveying, and hydraulic field testing would be executed to determine actual roughness coefficients for the pipes. However, the model calibration process is time consuming and requires a great deal of labor and data collection. For the purposes of this research, a full scale calibration for all 15 systems was not practical. As a result, the small changes made to the system to simulate realistic flow conditions were deemed adequate for this study. In addition, all of the changes made to the model database were considered reasonable alterations that did not result in unrealistic conditions for small water distribution systems.

2.3.3 Models Used in Study

The model database used in this research consists of 15 hydraulic models. Twelve of the models were initially developed as part of a previous study (Jolly et., al., 2013) with three additional models added as part of this study. In this study all 15 models were subsequently modified and analyzed for extended period simulations. While all the models represent actual distribution systems in Kentucky, each model was given a generic name in the form KY #. All identifying information for the actual systems represented by the models were removed, such as names of pumps and tanks, to protect the security of the utilities. In some cases additional pipes were added or deleted so as to disguise the source of the original datasets. Model names were grouped by configuration type. The first four models, KY 1 – KY 4, along with KY 13 are in the loop configuration. The layout of each system in the loop configuration is displayed in Figure 2.9.

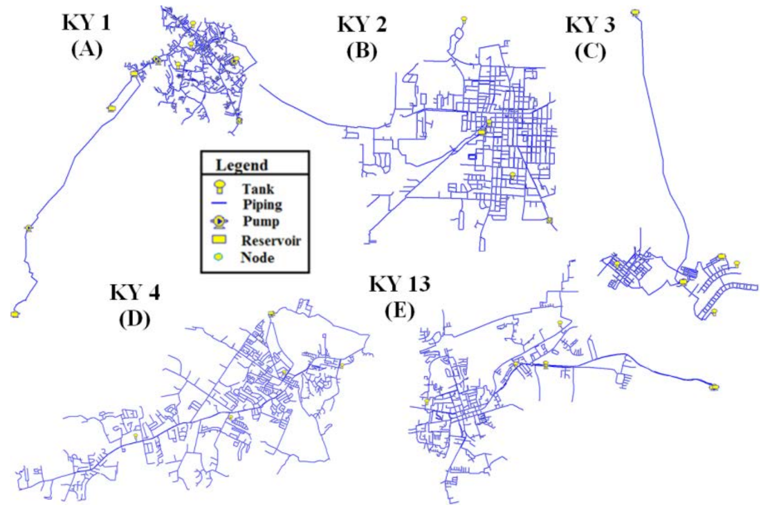


Figure 2.9: Loop Systems: (A) KY1; (B) KY2; (C) KY3; (D) KY4; (E) KY13.

Models KY 5 – KY 8, along with KY 14, are classified as models in grid configuration. The general layout of each system classified in the grid configuration is displayed in Figure 2.10.

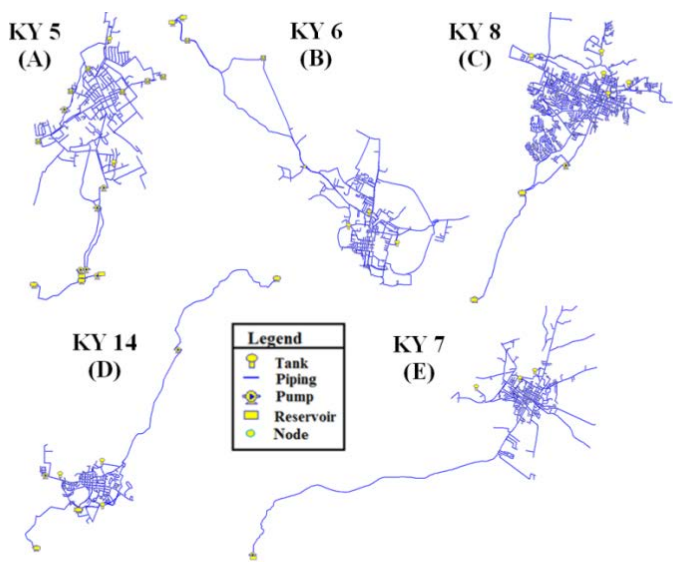


Figure 2.10: Grid Systems: (A) KY5; (B) KY6; (C) KY8; (D) KY14; (E) KY7.

The remaining models, KY 9 – KY 12 and KY 15, can be classified as branch configuration systems. Figure 2.11 displays the layout of each model in branch configuration.

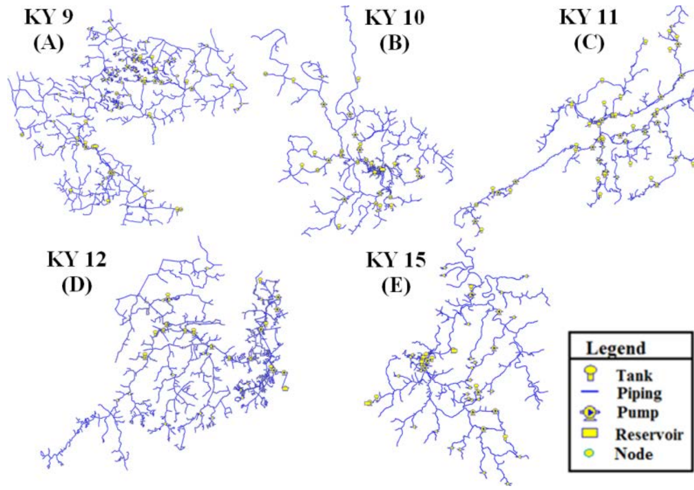


Figure 2.11: Branch Systems: (A) KY9; (B) KY10; (C) KY11; (D) KY12; (E) KY15.

2.4 Investigation of System Parameters

All 15 models are classified into three configurations, but each system has varying characteristics that distinguish them from other systems within the same configuration. The data displayed in Table 2.1 and Table 2.2 show differences in various system characteristics for all 15 systems.

Table 2.1: System Characterisitcs.

System	Configuration	Number of Tanks	Number of Pumps	Number of Nodes	Total Length of Pipes (mi)	Average Pipe Length (ft)
KY 1	Loop	4	7	796	103.6	606.4
KY 2	Loop	3	1	766	94.6	486.4
KY 3	Loop	3	5	279	56.7	858.1
KY 4	Loop	4	2	949	162.1	764.1
KY 13	Loop	5	4	733	93.4	582.6
KY 5	Grid	3	9	401	60.0	644.0
KY 6	Grid	3	2	521	76.5	677.64
KY 7	Grid	3	1	478	85.2	749.4
KY 8	Grid	5	5	1274	153.7	535.61
KY 14	Grid	3	6	349	64.5	699.0
KY 9	Branch	15	20	1142	597.7	2504.7
KY 10	Branch	13	13	921	267.2	1364.5
KY 11	Branch	28	21	795	285.4	1789.4
KY 12	Branch	7	16	2294	403.1	888.6
KY 15	Branch	8	13	613	299.5	2388.9

Table 2.2: System Characteristics (continued).

System	Configuration	Average Pipe Diameter (in)	Average Pipes/ Node	Demand (MGD)	Range in Elevation (ft)
KY 1	Loop	7.141	1.133	1.50	346.8
KY 2	Loop	5.713	1.341	2.09	96.0
KY 3	Loop	9.528	1.251	2.02	144.6
KY 4	Loop	7.020	1.180	1.51	249.4
KY 13	Loop	8.176	1.154	2.36	291.9
KY 5	Grid	8.638	1.155	2.28	333.7
KY 6	Grid	7.905	1.144	1.56	270.9
KY 7	Grid	7.709	1.240	1.53	211.6
KY 8	Grid	8.404	1.175	2.47	460.4
KY 14	Grid	9.644	1.395	1.04	359.0
KY 9	Branch	4.745	1.103	1.38	892.6
KY 10	Branch	5.637	1.123	2.26	470.0
KY 11	Branch	5.784	1.059	1.93	306.9
KY 12	Branch	4.597	1.044	1.38	205.7
KY 15	Branch	5.374	1.080	1.52	926.9

The data in Table 2.1 and Table 2.2 show that each system has a unique set of system characteristics. However, there are still trends present based on system configuration classification. From simple observation of the data, the branch systems have a greater number of tanks and pumps, and they also have greater total length of water lines than the other systems. It was desired to further investigate which system characteristics vary significantly from configuration to configuration.

2.4.1 Statistical Investigation of Trends Based on Configuration

In addition to the variation in layout and geometry of the water lines that distinguish systems between the three configurations, other characteristics may also help differentiate systems. In this study, five water distribution system models were created for each of the three configurations. Various system parameters were averaged for the five systems in each configuration, and this data is displayed in Table 2.3.

Table 2.3: Average System Characteristics.

System Parameter	Loop	Grid	Branch
Number of Tanks	3.8	3.4	14.2
Number of Pumps	3.8	4.6	16.6
Number of Nodes	704.6	604.6	1153
Total Length of Pipes (miles)	102.08	87.98	370.58
Average Length of Pipes (ft)	659.53	661.14	1787.23
Average Pipe Diameter (in)	7.516	8.651	5.227
Average Pipes/Node	1.212	1.222	1.082
Total System Demand (MGD)	1.896	1.776	1.694
Range of Elevations (ft)	228.7	262.7	622.3

Observation of data in Table 2.3 show some significant differences in certain system characteristics based on configuration. If it was proven that certain system parameters did vary systematically by configuration, these parameters could aid in classification of systems by configuration. Hypothesis testing was executed to test this theory and determine if there was a difference between population means, or a difference in the average values for the system parameters as system configuration varied. Specifically, a one-tailed two-sample t-test was used to test if there was no significant difference in the means or if one configuration had a significantly higher or lower value for a certain system parameter. Three tests were performed for each system parameter. The first tested the difference between the loop and grid systems, the second investigated the difference between the loop and branch systems, and the last examined differences in the grid and branch networks. The data was assumed to be independent and normal.

Because these system parameters will vary significantly based on the general size of the network, measured by the typical service demand (MGD), it was necessary to normalize the average system parameters by demand. Each system parameter was divided by the average daily demand (MGD) for that particular system before the values were averaged by configuration, resulting in an average value of the parameter per million gallon daily demand for each configuration. The average daily demand of all systems in the database ranged from one to three million gallons per day. The normalized averages of various system parameters are shown in Table 2.4, and these values are used in the hypothesis testing.

Table 2.4: System Parameters Normalized by Average Daily Demand.

System Parameter	Loop	Grid	Branch
Number of Tanks	2.1	2.0	8.3
Number of Pumps	2.1	2.7	10.3
Number of Nodes	394.9	334.7	742.5
Total Length of Pipes (miles)	57.9	51.1	237.7
Average Length of Pipes (ft)	362.9	419.1	1112.3
Average Pipe Diameter (in)	4.065	5.498	3.159
Average Pipes/Node	0.657	0.773	0.662
Range of Elevations (ft)	128.774	160.481	381.430

The null hypothesis (H_o) states that the means (μ) of the two populations are equal (H_o: $\mu_1 = \mu_2$), and the alternative hypothesis (H_a) states that one of the population means are higher (H_a: $\mu_1 > \mu_2$ or H_a: $\mu_1 < \mu_2$). The specific alternative hypothesis used was determined by examining the means of the system parameters in Table 2.4. The configuration with the higher value of the system parameter in question was hypothesized to have the higher population mean in the alternative hypothesis. For example, when performing the test for the number of tanks between the loop and branch systems, the alternative hypothesis stated that μ_1 (mean for loop systems) was less than μ_2 (mean for branch systems) since loop systems averaged 2.1 tanks per MGD demand and branch networks averaged 8.3 tanks per MGD demand. Table 2.5 shows the alternative hypotheses for the t-tests performed (the null hypothesis for all tests states that the two population means are equal).

Table 2.5: Alternative Hypotheses.

System Parameter	$Loop_1$ & $Grid_2$	$Loop_1$ & $Branch_2$	$Grid_1$ & $Branch_2$
Number of Tanks	$\mu_1 > \mu_2$	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$
Number of Pumps	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$
Number of Nodes	$\mu_1 > \mu_2$	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$
Total Length of Pipes (miles)	$\mu_1 > \mu_2$	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$
Average Length of Pipes (ft)	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$
Average Pipe Diameter (in)	$\mu_1 < \mu_2$	$\mu_1 > \mu_2$	$\mu_1 > \mu_2$
Average Pipes/Node	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$	$\mu_1 > \mu_2$
Total System Demand (MGD)	$\mu_1 > \mu_2$	$\mu_1 > \mu_2$	$\mu_1 > \mu_2$
Range of Elevations (ft)	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$

A one-tailed two-sample t-test was performed for each comparison in this study. The population variances were not assumed to be equal, so Equation 2-1 was used to calculate the t value (Dielman, 2005).

$$t = \frac{\overline{y_1} - \overline{y_2}}{\sqrt{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)}} \tag{2-1}$$

where $\bar{y}$ is the mean of the sample (shown in Table 2.4), s represents the standard deviation of the sample, and n is the number of data points in the sample. The value for n was five for all cases because there were five systems for each system configuration. After the t statistic was calculated for each hypothesis test, the critical t value ($t_{\alpha,df}$) was interpolated from a t distribution table. In order to find the necessary critical value for each test, the calculated degrees of freedom for each comparison were required along with the desired alpha value. For this study, a significance level of $\alpha = 0.05$ was used, implying 95% confidence in the decision. Decision guidelines were then used to determine if the null hypothesis should be rejected. If the null hypothesis is not rejected, there is not sufficient information to conclude that there is a difference in sample means (at the α=0.05 significance level). If the null hypothesis is rejected, there is sufficient evidence to conclude that one sample mean is higher than the other (at the α=0.05 significance level). The decision guideline for the t-test differs based on the alternative hypothesis used. The decision rules and the interpretation of the decision are shown in Table 2.6.

Table 2.6: Decision Rules and Interpretation of t-tests.

Alternative Hypothesis	t vs. $t_{\alpha,df}$	Decision	Interpretation
$\mu_1 > \mu_2$	$t \leq t_{\alpha,df}$	Do not Reject H_o	No difference in parameter
	$t > t_{\alpha,df}$	Reject H_o	$Configuration_1$ has higher value for parameter than $configuration_2$
$\mu_1 < \mu_2$	$t \geq - t_{\alpha,df}$	Do not Reject H_o	No difference in parameter
	$t < - t_{\alpha,df}$	Reject H_o	$Configuration_1$ has lower value for parameter than $configuration_2$

The interpretation of the results of the hypothesis tests are shown in Table 2.7. An "L" represents loop systems, "G" is for grid systems, and "B" represents branch networks. If the letters are equal, the null hypothesis was not rejected and there is not enough evidence to prove a difference in the system parameters. If an inequality sign is present, the null hypothesis was rejected and there was enough evidence to conclude that one configuration had a higher value for the system parameter at the 5% significance level. For example, the "L<B" shown for the test for number of tanks between the loop and branch system indicates that the loop systems did have a statistically significant lower average for the number of tanks (per MGD demand) than the branch systems.

Table 2.7: Results of Hypothesis Tests.

System Parameter	Loop & Grid	Loop & Branch	Grid & Branch
Number of Tanks	L=G	L<B	G<B
Number of Pumps	L=G	L<B	G<B
Number of Nodes	L=G	L=B	G=B
Total Length of Pipes (miles)	L=G	L<B	G<B
Average Length of Pipes (ft)	L=G	L<B	G<B
Average Pipe Diameter (in)	L=G	L>B	G=B
Average Pipes/Node	L=G	L=B	G=B
Range of Elevations (ft)	L=G	L<B	G<B

Results show that there is not a significant difference in means for any of the system parameters between the loop and grid systems. However, there is a statistically significant difference in means for several system parameters tested between the loop and branch systems and between the grid and branch systems. The loop and grid systems had lower values than branch systems for the number of tanks, number of pumps, total length of water lines, average length of water lines, and the range in elevation of system components. The branch systems had lower average pipe diameters than the loop systems, but not lower than the grid systems. There was no difference in number of nodes and average pipes per node between loop and branch and between grid and branch systems.

Results proved that loop and grid systems had significantly lower ranges in elevation of system components than branch systems, although there was no significant difference between loop and grid systems. This concept was expanded to further investigate if differences in system parameters, such as number of pumps or total length of water lines, had any correlation with topography of the area (hilly vs. flat regions). A t-test at the alpha=0.05 significance level was performed to compare each system parameter with the range in elevation for the system to conclude if there was a linear relationship between elevation range and the various system parameters.

These tests were first performed by grouping the data by system configuration, so each test consisted of five data points. It was found that there was no linear relationship between elevation range and any system parameter, with the exception of the average pipes per node parameter for loop systems, when the data was grouped by configuration. The t-tests were also performed for elevation range vs. system parameter with all 15 systems grouped together. Results showed that there was a linear relationship between range in elevation and number of tanks, number of pumps, total length of pipes, average pipe length, average pipe diameter, and average pipes per node. There was no linear relationship between elevation range and number of nodes. Therefore, it is not certain if the variation in system components is directly caused by the range in elevation of the system. There was found to be a significant difference in elevation range between loop/grid systems and branch systems, so the correlation found between elevation range and the parameters while considering all systems could be a result of these differences. All data and equations used in statistical testing are shown in Appendix A.

2.4.2 Interval Estimates for System Parameters by Configuration

In order to use these results as a tool to aid in correct classification of networks by general configuration, confidence intervals were developed for various system parameters. These confidence intervals provide ranges that the values of the network parameters (normalized by average demand in MGD) will likely fall between for each general configuration. The user will be able to gather information about the geometry of their system, divide these parameters by average daily demand, and attempt to place the resulting values in a range for a certain configuration.

Because the hypothesis testing was not able to prove statistically significant differences in all of the system parameters by configuration, many of the confidence intervals will overlap for certain parameters and system configurations. Even though these ranges may still be helpful, the ranges given for system parameters that proved to be significantly different based on configuration will be most helpful in classifying systems. The confidence intervals were developed using the systems means for parameters normalized by the average daily demand (in MGD) for each system. A 95% confidence level was used, meaning we are 95% confident that the actual value of the parameter for a given system will fall in the given range. The confidence intervals for various system parameters (normalized by the average daily demand in MGD for each system) for loop, grid, and branch configured systems are shown in Table 2.8.

Table 2.8: Confidence Intervals for System Parameters by Configuration.

System Parameter (per MGD demand)	Loop		Grid		Branch	
	Low	High	Low	High	Low	High
Number of Tanks	1.55	2.60	1.53	2.51	4.59	11.99
Number of Pumps	0.73	3.52	0.90	4.58	7.37	13.14
Number of Nodes	226.9	562.8	228.7	440.7	264.5	1220.6
Total Length of Pipes (mi)	30.3	85.4	38.0	64.1	125.8	349.5
Average Pipe Length (ft)	258.8	467.1	261.8	576.4	628.8	1595.8
Average Pipe Diameter	3.259	4.871	3.268	7.360	2.788	3.531
Average Pipes/Node	0.555	0.760	0.468	1.079	0.546	0.779

2.5 Analysis and Discussion

The results of the hypothesis testing provide important information about the differences in systems classified as different configurations. Systems are predominantly classified based on the geometry and layout of the water lines, sometimes considering the diameter of water lines in certain areas of the system when trying to differentiate between loop and grid systems. However, these proven differences in system parameters could also aid in classifying networks into configurations. Results of the hypothesis testing show that loop systems have higher average pipe diameters than branch systems. However, hypothesis testing was not able to prove that grid systems also have higher average pipe diameters than branch networks. Branch systems typically have a higher number of tanks and pumps than loop and grid systems, and branch systems also have greater lengths of total water lines and average pipe lengths over loop and grid systems. The hypothesis testing was not able to prove any differences in the number of nodes or average pipes per node among the system configurations.

Branch systems are typically present in rural areas where the service area is fairly large. Some customers in the far branches are spaced far apart from each other, and the dead-end portions of the network provide their water supply. In contrast, loop and grid systems are common in large municipal areas or densely populated areas. The less dense, more spread out configuration of branch systems explains the increased number of tanks and pumps over loop and grid systems even though the total system demand is similar. The large area branch systems serve require more tanks and pumps to provide water storage and pressure. The higher total length of pipes in the system is also explained by the large coverage area for branch systems. Even though water lines in branch systems typically aren't as dense, they must provide flow for a significantly larger area. The argument is similar to explain the higher average length of water lines in branch systems; many long pipes are required to deliver flow to the far branches.

Even though branch systems usually contain a greater total length of water lines than other system configurations, the average diameter of these pipes are typically smaller. Because many customers in branch systems are spread out, less flow needs to be conveyed through the pipes. This is especially true for consumers in the far branches;

very few people may be requiring water supply from these pipes. Locations of customers are typically denser in loop and grid systems, requiring a significant flow to travel through the pipes. Hypothesis testing was able to prove that loop systems had higher average pipe diameters than branch systems, but it was not proven that grid systems had a significantly higher average pipe diameter than branch networks. The five grid systems did have a significantly higher average pipe diameter than that of branch systems, but the high standard deviation calculated for the grid systems likely resulted in the decision to not reject the null hypothesis.

The argument could be made that the branch systems had a higher number of tanks/pumps, etc. simply because these systems serve a larger population and had a higher total demand. However, all of these networks had an average demand between 1 and 3 MGD, and hypothesis tests were also conducted to test if there was a significant difference in system demand among the configurations. Hypothesis testing (one-tailed two-sample t-test at the 5% significance level) found no significant difference among the system configurations for the total system demand. Furthermore, all system parameters were normalized by dividing the parameters by the average daily demand (in MGD) for each system. This resulted in a set of parameters measured per million gallons of daily demand. Therefore, slight variations in system demand did not have an effect on the system parameters.

It could also be argued that some differences in system parameters could be explained by variation in the range of elevations that a system serves. It was proven that branch systems did serve areas with higher ranges of elevations than loop and grid systems. When t-tests were performed to investigate if there was a relationship between individual parameters and range in elevation with the data grouped by configuration, there were no strong relationships present. However, when this relationship was investigated for all 15 systems grouped together, there was a linear relationship found between elevation range and all of the mentioned systems parameters (excluding number of nodes). Some of these differences in system parameters based on configuration could partially be a result of the range in elevation of system components. However, it is not certain since branch systems typically have a higher elevation range than loop/grid systems and it is unclear if there is direct causation.

This discussion is helpful in understanding the fundamental differences in system configurations. These differences in various system parameters can also be utilized in future research relating to security of water distribution systems. As an expansion of this research, models in the database are used in sensor placement software to test guidance in placement of water quality sensors. The recommended sensor locations from the sensor placement software can be examined to determine if patterns exist based on general system configuration or certain system parameters such as total length of water lines or number of tanks. If trends in the placement of sensors are observed based on system configuration, the differences in system parameters discussed in this study can be used as tools to develop guidance to assist small utilities in placing water quality sensors. Development of sensor placement guidance, without the need for a costly calibrated hydraulic model, would be greatly beneficial to a small utility in protecting their water supply.

CHAPTER 3

3 Sensor Placement Guidance for Small Utilities

3.1 Introduction

Water distribution systems are an integral part of society, and the availability of a clean and dependable supply of water influences both the socioeconomic status and health of a populace. In recent years, protecting the nation's critical infrastructure from terrorist attacks has become a priority, and efforts to protect the water infrastructure are included in this goal. 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 (Hart & Murray, 2010). In an effort to mitigate the risks from intentional or accidental contamination of the water supply, contamination warning systems (CWS) have been proposed as a cost-effective and reliable strategy.

Contamination warning systems are proactive strategies to reduce public health impacts and economic loss from a contamination event in a distribution system by providing an early indication of intentional or accidental contamination (Janke et al., 2006). A CWS includes deployment and operation of online sensors, which involves a network of sensors that can assess the quality of water in the distribution system and alert an operator of a potential contamination event. The challenge involved with developing these water quality monitoring systems is determining which locations are best suited for deployment of sensors. Budget constraints will limit the number of sensors a utility can deploy, and they must be placed in locations that maximize their ability to detect contamination events and provide the greatest protection of human health (McKenna et al., 2006).

To date, there is no applicable federal or state guidance to assist utilities in the deployment of water quality sensors. Technological advancements in sensor placement optimization software may help solve the problem of sensor placement issues for some utilities. 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 (Berry et al., 2010). While TEVA-SPOT uses public domain software (e.g. EPANET) along with a sophisticated optimization algorithm to evaluate the ability of different sensor combinations to detect contamination events, the software can be intimidating to use for medium to small utilities. As a result, application of the software has largely been limited to large utilities or research studies. This paper proposes the use of a fairly simple enumeration method coupled with a widely used commercial network distribution model (i.e. KYPIPE) for applications of sensor placement to small or medium sized utilities. For the purposes of this discussion, KYPIPE was primarily used in order to facilitate access and generation of a dataset of network models from a statewide database. The proposed heuristic can be easily adapted for use with EPANET directly or with any other commercial software.

In order to evaluate the proposed heuristic, the model is applied to 12 different water distribution systems associated with small water utilities in Kentucky (Jolly et al., 2013). The model is executed with a variety of contamination scenarios for all systems, placing a number of sensors reasonable for the budget of a small utility. The results of these applications are then compared to the results obtained from applying TEVA-SPOT to the same 12 systems. In each case, sensor locations are selected by minimizing the time to detect the contaminant.

3.2 Current Sensor Placement Software

The Threat Ensemble Vulnerability Assessment Sensor Placement Optimization Tool (TEVA-SPOT) Program was developed as a probabilistic framework for analyzing the vulnerability of drinking water distribution networks (Murray et al., 2004). This collection of software tools to aid utilities in the design of sensor networks was developed by researchers from the Environmental Protection Agency (EPA), Sandia National Laboratories, the University of Cincinnati, and Argonne National Laboratory (Murray et al., 2010). TEVA-SPOT creates a threat ensemble, consisting of a set of contamination scenarios, and the vulnerability of the network is assessed using the entire threat ensemble (Murray et al., 2004).

TEVA-SPOT contains three main software modules. The first module simulates the set of incidents in the threat ensemble, the second module calculates the potential consequences of each incident, and the third module optimizes for sensor placement. The design basis threat consists of the set of incidents for the sensor network to detect. The consequences are calculated based on one or more of the performance objectives that include the number of people who become ill as a result of exposure, percentage of incidents detected, time to detection, and length of pipe contaminated. When TEVA places sensors, the mean consequence for a given objective is minimized. This is equivalent to assuming that each contamination scenario is equally likely to occur and that each is important when selecting sensor locations. The user is able to specify weights to put more importance on locations with a higher likelihood of being contaminated (Murray et al., 2010). A flow chart of the TEVA-SPOT software is shown in Figure 3.1.

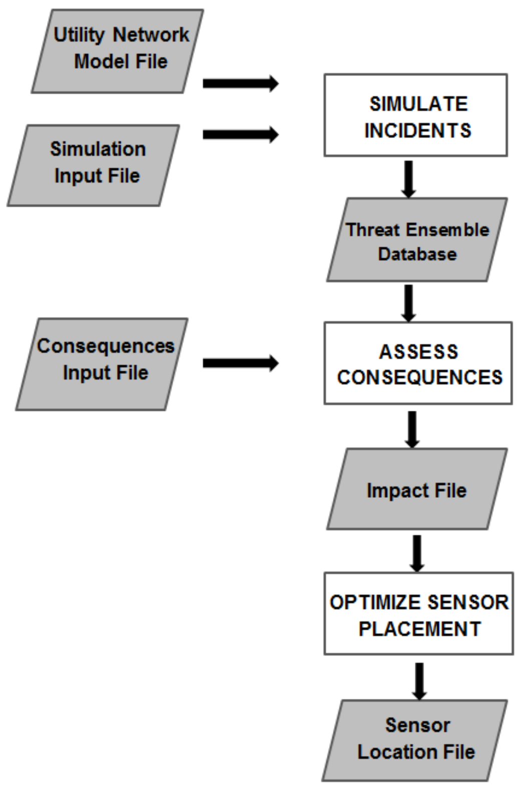


Figure 3.1: Flowchart of TEVA-SPOT Software (Murray et al., 2010).

TEVA uses simulation and optimization models to select optimal placement of sensors for a CWS by implementing two steps: modeling and decision-making. The modeling process first involves creating a network model for a hydraulic and water quality analysis. TEVA-SPOT uses EPANET (U.S. EPA, 2008) to perform these analyses. The modeling process also must include the following steps: describing sensor characteristics, defining the design basis threat, setting up performance measures, defining utility response to sensor detection events, and finally identifying potential sensor locations (Murray et al., 2006). The decision making process uses an optimization method and evaluates sensor placement. This step is performed by analyzing trade-offs and comparing a set of designs to account for modeling and data uncertainties (Murray et al., 2008).

The first step in the modeling process, developing a network model as input to a hydraulic and water quality modeling software, is critical. An EPANET INP file is used to describe the physical characteristics of the system, and this file is built using the EPANET user interface. Using models for the purpose of contamination warning systems requires a high degree of accuracy. Characteristics of the sensor behavior are also needed to measure performance of a CWS, so the sensor type, detection limit, and accuracy should be included (Murray et al., 2008).

The design basis threat describes the type of threat that the utility wants to protect against when designing a contamination warning system. Contamination incidents are described by the specific contaminant, the quantity and duration of injection of the contaminant, and the locations where the contaminant is introduced. The program understands that these conditions cannot be known before an incident occurs, so the modeling process takes this uncertainty into account. For example, probabilities can be assigned to each node in a system to specify the likelihood that contamination would occur at that location. An ensemble of incidents is then simulated, and sensor network designs are chosen based off how they perform for the entire ensemble of incidents (Murray et al., 2008).

TEVA measures performance of sensor network designs based on minimizing certain performance objectives including the number of failed detections, extent of contamination, mass/volume consumed, and time to detection (Murray et al., 2010). If a utility has several important priorities for the performance of their sensor design, multiple objectives can be considered by assigning a relative importance, or weight, to each objective. Modeling the utility response time, the time between initial detection of the contaminant and effective warning of the population, is another important aspect of the modeling process (Murray et al., 2010). The user must also input information defining all potential sensor locations in the system. When selecting nodes for potential sensor locations, certain requirements are needed such as accessibility, security, and protection from the environment. A longer list of feasible sensor sites results in a sensor design that is more likely to perform well. The benefits of using sites that need some adaptation to meet requirements may be worth the additional costs, but sensor placement can be restricted to locations preferred by the utility (Murray et al., 2008).

The second main step in the TEVA sensor placement framework is the decision process. The goal of this step is to aid utilities in understanding the public health and cost tradeoffs between different sensor placement designs and ultimately help them choose the sensor design that will best meet their needs. This is accomplished by using an incremental approach for applying optimization to generate a set of sensor placement designs that can be compared and contrasted. The first sensor placement design is found under ideal conditions with simplifying conditions. The assumptions are then removed one at a time to make the designs more realistic. For example, simplified conditions would assume all nodes in the system as potential sensor locations, instantaneous response time, and perfect sensors. More realistic conditions would assume delayed response time and would force sensors to be placed at utility-owned or public locations (Murray et al., 2006). The performance of the new sensor design is compared with the previous designs and baseline case with no sensors, quantitatively and visually, to understand what has been gained or lost with each assumption (Murray et al., 2010). The tradeoffs can be analyzed in terms of the desired performance objective, such as the percent reduction in the number of illnesses with each design. The decision making step uses the contamination warning system model to evaluate a series of sensor network designs in a systematic way (Murray et al., 2008).

TEVA-SPOT provides three optimization method options in order to develop a sensor design: mixed-integer programming (MIP), a greedy randomized adaptive search procedure (GRASP) heuristic, and a Lagrangian relaxation method. The standard formulation used to evaluate impacts is a Mixed Integer Program (MIP) formulation, which optimizes linear objective functions by maximizing or minimizing the function subject to constraints. The MIP solver minimizes the predicted impact of an ensemble of contamination events using the specified sensor set size. This solver is exact and will guarantee to find the optimal solution (Murray et al., 2010). MIP technology can be used if the problem instances are not very large and if sufficient power is available. However, heuristic methods are commonly used when working with large problem instances because the number of constraints and variables will grow rapidly as problem size increases (Berry et al., 2006).

The GRASP algorithm finds solutions by systematically exploring the space of possible sensor layouts, and it typically produces solutions as effective as results from a MIP in less time. This solver was utilized to collect data in TEVA-SPOT for this study. The GRASP randomly creates a set of starting points using greedy bias to make these reasonable approximations. It then explores ways to move one sensor to a new location that will improve the objective function, making these swaps until a better solution doesn't exist. The only limitation of this method is that it still has a fairly large memory requirement.

The Lagrangian method removes a set of "difficult" constraints, resulting in a problem that is easier to solve. Penalties are then added to the objective function to satisfy the relaxed constraints. Penalty weights are manipulated and an iterative algorithm drives the solution to feasibility (Murray et al., 2010). A summary of the three solvers, including the function and characteristics of each solver, is shown in Table 3.1.

Table 3.1: Solvers Used in TEVA-SPOT (Berry et al., 2010).

Solver	Function	Characteristics of Solver
PICO Mixed Integer Program (MIP) solvers	Uses MIP formulations to determine global optimal solutions	Large problems can cause computationally expensive process or cause size of MIP to become too large
Grasp Heuristic	Performs sensor placement without explicit creation of MIP formulations	Uses less memory than MIP and runs with low computation time
Lagrangian Heuristic	Uses MIP formulation to find near optimal solutions	Computes lower bound of best solution

3.3 KYPIPE Sensor Placement Tool

KYPIPE was first developed in the 1970s to calculate steady state flows and pressures in a water distribution system (Wood, 2010). The program can complete an analysis for any configuration of pipes including hydraulic components such as pumps, valves, fittings with significant head losses, and storage tanks. The program also has the capabilities to execute an extended period simulation (EPS) that can account for the variation in storage tank levels over time (Wood, 2010). KYPIPE performs hydraulic analyses using the KYPIPE hydraulic engine which is based on a nonlinear solution of the network loop energy equations (Wood & Rayes, 1981).

The Water Quality Sensor Placement Tool has been developed to work with the existing KYPIPE graphical user interface. The goal is to provide a simple tool to aid utility managers in the optimal placement of sensors in their distribution systems. The simplicity and ease of use of the tool makes it attractive for use in small utilities. The sensor placement tool recommends optimal sensor placement, regardless of how many sensors are implemented, based on minimizing time to detection. The tool considers detection events at nodes throughout the entire system, and recommends optimal sensor placement based on the locations that can detect contamination events the fastest.

The KYPIPE sensor placement routine utilizes four different input files. The first input consists of a normal KYPIPE input file. This file is used to describe the physical parameters of the network and to specify the parameters for the required extended period simulations. The second file is an EPANET INP file that is generated internally within KYPIPE using data from the normal KYPIPE data file. Some adjustments are made to accommodate differences in the way the two programs handle certain components such as pumps (i.e. nodes vs. links). The third file is the travel time matrix, which is generated using hydraulic and water quality calculations. The fourth file is used to prescribe the parameters associated with the sensor placement algorithm. Figure 3.2 displays the entire procedure executed by the KYPIPE WQ Sensor Placement Tool, followed by further explanation of the process.

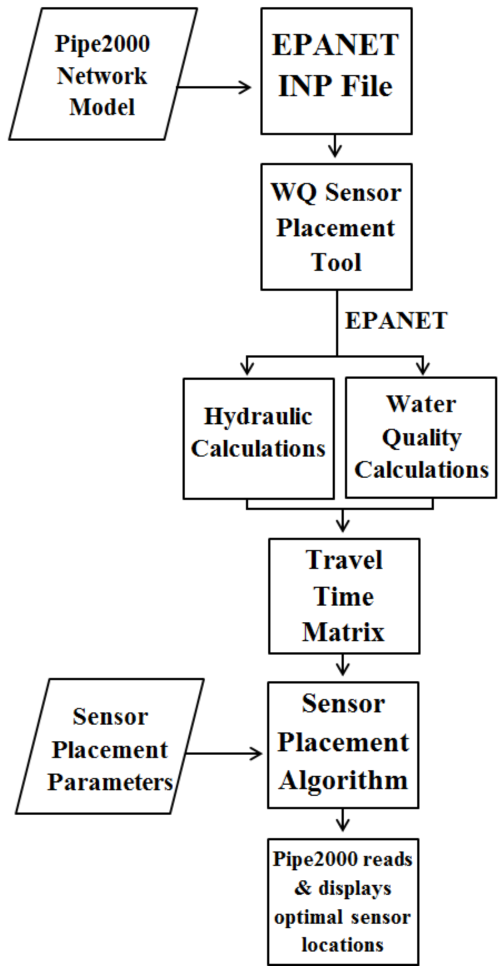


Figure 3.2: Flowchart of KYPIPE Sensor Placement Methodology.

When performing a sensor placement analysis, KYPIPE utilizes the EPANET engine for both hydraulic and water quality calculations. Therefore, use of the sensor placement tool will first require KYPIPE to export the network model into EPANET format (INP file) that contains all hydraulic and water quality data. KYPIPE then makes calls to the EPANET engine to perform the hydraulic and water quality analyses, and result files are generated to the hard drive. The tool also uses this data to generate the travel time matrix, which is used to perform the optimal sensor placement calculations.

The optimal sensor location information is written to a file on the hard drive, and KYPIPE is able to read the file and display the chosen sensor locations on a graphical representation of the water distribution network. KYPIPE is also able to read the results files and display data from the hydraulic and water quality analyses. Figure 3.3 shows the steps to be carried out by the user in order to execute the sensor placement tool in KYPIPE.

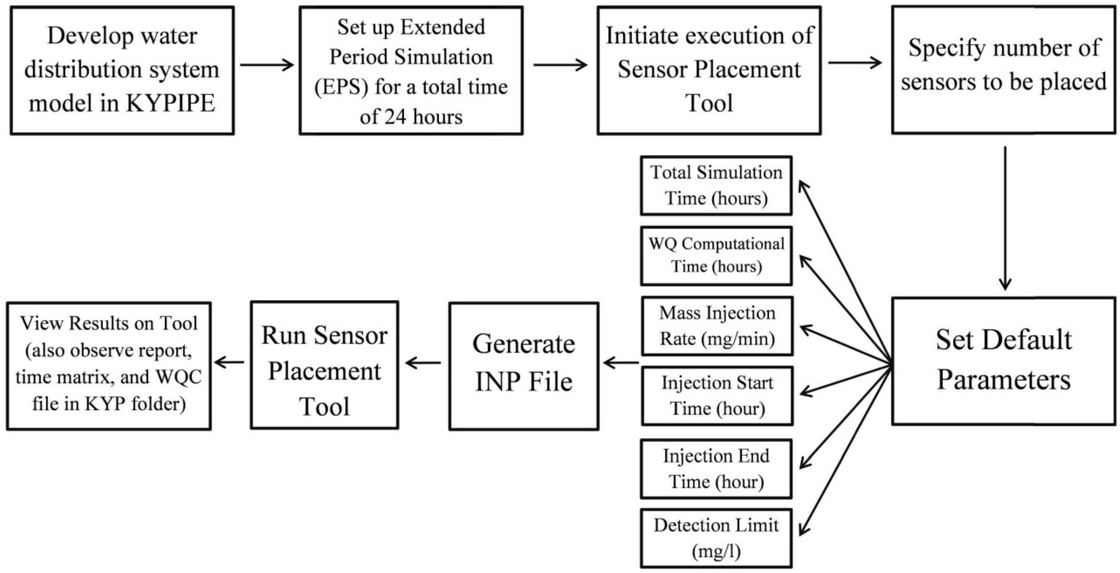
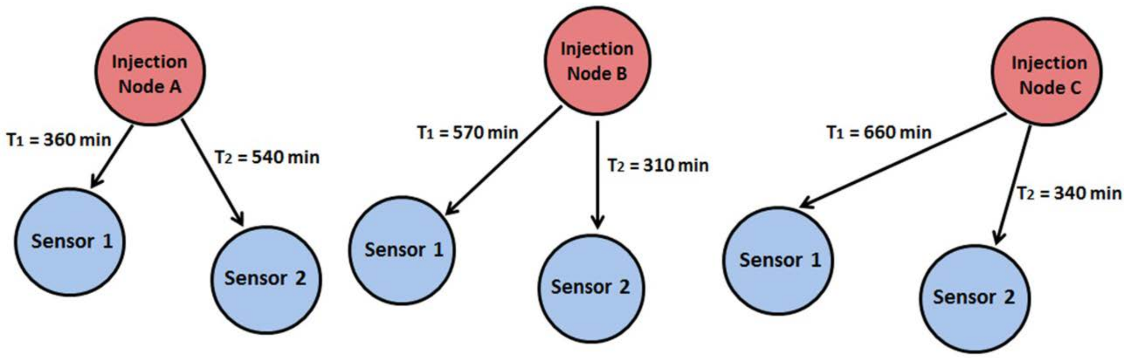


Figure 3.3: Sensor Placement Tool Flowchart.

For the case where only one sensor is being considered, the algorithm simply iterates through all combinations of injection points and all possible sensor locations. This results in a matrix of travel times between the injection location and possible sensor node. The algorithm then simply enumerates through the set of solutions to find the "optimal" sensor location (with the lowest average time to detection). Because the algorithm computes the travel times for all sensor locations, it is also possible to list the average time to detection for each sensor location, thus providing the user with alternative options in the event the "optimal" sensor turns out to be impractical for other secondary conditions (e.g. physical access, communication or power limitations, etc.).

For situations involving multiple sensors, the algorithm calculates the average travel time for each set of sensor locations. As with the single case, these results are then stored in a matrix of travel times for each combination of multiple sensors. The methodology for determining the average travel time for two sensors is illustrated in Figure 3.4. The contaminant is “injected” at the first possible injection site, and the travel time for the contaminant to reach each of the sensors in the first sensor combination is determined. The values for T_1 and T_2 represent the travel times from each injection node to sensor 1 and sensor 2, respectively. The travel time assigned to this particular set of sensor locations and injection node will be the minimum of the two travel times, since the contaminant is considered to be detected when it reaches the first sensor. This process is repeated for all possible injection nodes in the system. The average travel time for the particular set of sensor locations is calculated by averaging the minimum travel times from all injection sites. The sum of travel times from all injection sites is calculated and divided by the total number of injection nodes to determine the average travel time for the set of sensor locations.



$$Travel\ Time = \frac{\sum Minimum\ Travel\ Times}{\#\ of\ Injection\ Nodes} = \frac{(360+310+340)\ min}{3} = 336.67\ minutes$$

Figure 3.4: Sensor Placement Tool Theory.

This process is then repeated for every possible set of sensor locations, resulting in an average travel time for every possible combination of two sensors in the system. The sensor combination with the lowest average travel time will be considered the optimal sensor location. As with the single sensor case, the user may display the travel times for all the sensor location combinations if desired, thereby providing information on inferior solutions as well.

It should be recognized that use of an optimization algorithm based on complete enumeration will result in an exponential increase in the evaluation of combinations of travel times as one considers more than one sensor. However, many small and even medium sized systems may not have the financial resources to place a large number of sensors across the network. Thus the ability to site a smaller number of sensors (e.g. 2 to 3) may be sufficient to provide adequate coverage for such systems. As system become larger, it is likely that they may contain multiple pressure zones. In such cases the proposed algorithm may be then be applied to each pressure zone individually, thereby limiting the computational burden while providing for more sensors. Finally, the ability to obtain and display the complete solution space for the problem may allow the utility to identify sub-optimal sites that may still be able to provide for expanded protection for the utility.

In order to maximize the potential coverage of the sensor locations, the KYPIPE Sensor Placement Tool considers all nodes to be potential sensor locations (i.e. including tanks, pumps, reservoirs, and junctions). However, the algorithm excludes all dead-end nodes as possible sensor locations. The average travel time to dead-end nodes will generally be much higher, skewing the average times to detection. Possible injection sites are considered to be all non-zero demand nodes, excluding dead-end nodes. Dead-end nodes are considered to be consumption nodes, so any contaminant injected at these nodes is assumed to be consumed immediately and the contaminant will not be able to travel further in the system.

The contamination detection limit for each sensor is entered in the default parameters menu for the program (a detection limit of 0.01 mg/l was used in this study). When the concentration of the contaminant reaches 0.01 mg/l at the particular sensor node, the contaminant is considered to be detected. The tool considers 24 hours as the maximum travel time. Any travel time past 24 hours will be considered 24 hours for calculation purposes.

As indicated previously, TEVA-SPOT provides the user with several different design options (i.e. minimize number of failed detections, extend of contamination, mass/volume consumed, or time to detection). In order to minimize the computational burden and maximize use of the algorithm from small to medium sized systems, the KYPIPE Sensor Placement Tool considers minimum time to detect as the sole operational objective.

3.4 Water Distribution System Models

In order to demonstrate the utility of the proposed approach to the sensor placement problem, the sensor placement software was evaluated using a database of 12 small water distribution system models (Jolly et al., 2013). While each of the models represent a real distribution system in Kentucky, all models were given a generic name in the form KY #.

All identifying information for the actual systems represented by the models was removed, such as names of tanks, to protect the security of the utilities. Model names were grouped by physical configuration type (Von Huben, 2005). The first four models, KY 1 – KY 4, are characterized as loop systems. Models KY 5 – KY 8 are classified as grid systems, while the remaining models, KY 9 – KY 12, are characterized as branch systems. The layout of one system representing each of the three configurations is displayed in Figure 3.5.

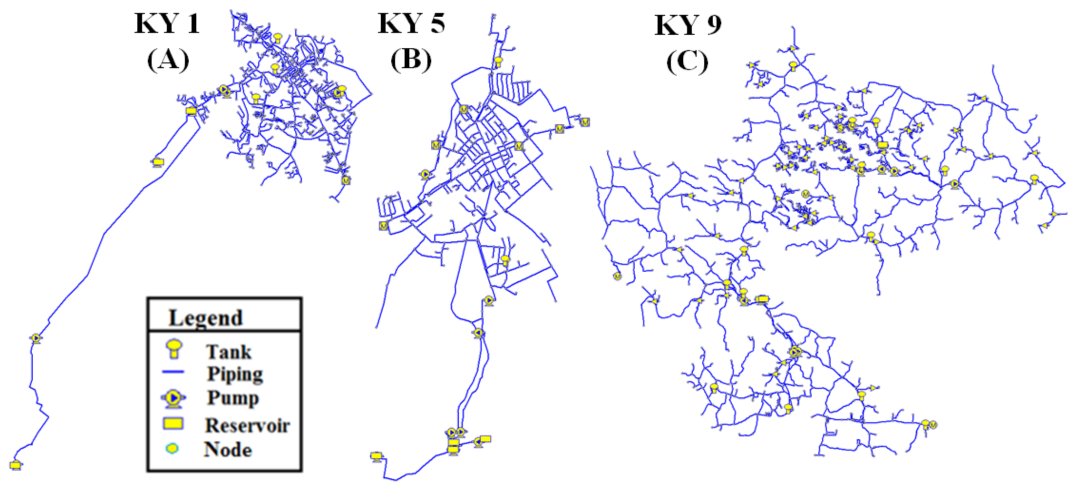


Figure 3.5: System Models (A) Loop; (B) Grid; (C) Branch.

3.5 Verification Studies

3.5.1 Contamination Scenarios

In order to evaluate the performance of the KYIPE Sensor Placement Tool and to compare its performance against TEVA-SPOT, the tool was executed on the 12 hydraulic models for 15 different contamination scenarios. The contamination scenario is determined by both the rate of injection of the contaminant (in mg/min) and the total injection time (in hours). Contamination scenarios were created for three different general scenarios: fixed amount, fixed rate, and fixed time. Each general scenario is comprised of five specific sets of an injection rate with a total injection time.

For the fixed amount scenarios, the scenario simulates a drum of contaminant to be injected, and it is desired to inject the entire drum. The pump speed used to inject the contaminant can be varied and unlimited time is available. The fixed rate scenarios simulate an injection pump with a constant speed, so injection rate cannot be varied.

However, unlimited time and materials (contaminant) is available. The fixed time scenarios model a limited amount of time available to inject the contaminants, but the pump speed can be varied and supplies are unlimited. The 15 contamination scenarios performed on each model are displayed in Table 3.2.

Table 3.2: Contamination Scenarios.

	Injection Rate (mg/min)	Injection Time (hours)	Total Contaminant Injected (g)
Fixed Amount (Vary Time)	4000	1	240
	2000	2	240
	1000	4	240
	500	8	240
	250	16	240
Fixed Rate (Vary Amount)	1000	1	60
	1000	2	120
	1000	4	240
	1000	8	480
	1000	16	960
Fixed Time (Vary Rate)	600	4	144
	800	4	192
	1000	4	240
	1200	4	288
	1400	4	336

All 15 contamination scenarios were executed on each of the 12 water distribution system models using both TEVA-SPOT and KYPIPE (results of all simulations are shown in Appendix E). It was desired to compare the sensor placement results, both sensor placement location and times to detection, between KYPIPE and TEVA-SPOT for a variety of scenarios. To be able to directly compare results from the two sensor placement programs, it was required that all parameters matched between the programs. First, the general network models used in each comparison were identical. The TEVA-SPOT program uses a model input from EPANET. Even though minor differences exist between KYPIPE and EPANET, all major system components and characteristics of these components matched between the two programs. An example of a difference between KYPIPE and EPANET is that KYPIPE allows tanks to be measured as a total volume or fixed diameter, while EPANET only allows a fixed diameter as input for tank size. To make the models as similar as possible, all tanks in both KYPIPE and EPANET were set as fixed diameters.

Parameters used in the sensor placement tool in KYPIPE and TEVA-SPOT were also standardized. The WQ computational time (labeled as the hydraulic timestep in TEVA-SPOT) was set to 60 seconds, and the total simulation time was set to 24 hours. The detection limit for both programs was also set to 0.01 mg/l. This ensured one program would not detect the contaminant faster than the other simply because it had a lower detection limit. As mentioned, the KYPIPE sensor placement tool utilizes the EPANET engine to perform hydraulic and water quality calculations. This further reduces any differences in the programs prior to sensor placement optimization.

3.5.2 Comparison of Times to Detection

The baseline contamination scenario (considered the baseline case because it was present in all three general contamination scenarios) injected a contaminant at 1000 mg/min for four hours. The comparison of time to detection between the two programs using the baseline condition for the placement of one sensor is shown in Figure 3.6. Because the time differences between the nodes selected by TEVA-SPOT and KYPIPE are minimal, the percent differences in times are also displayed.

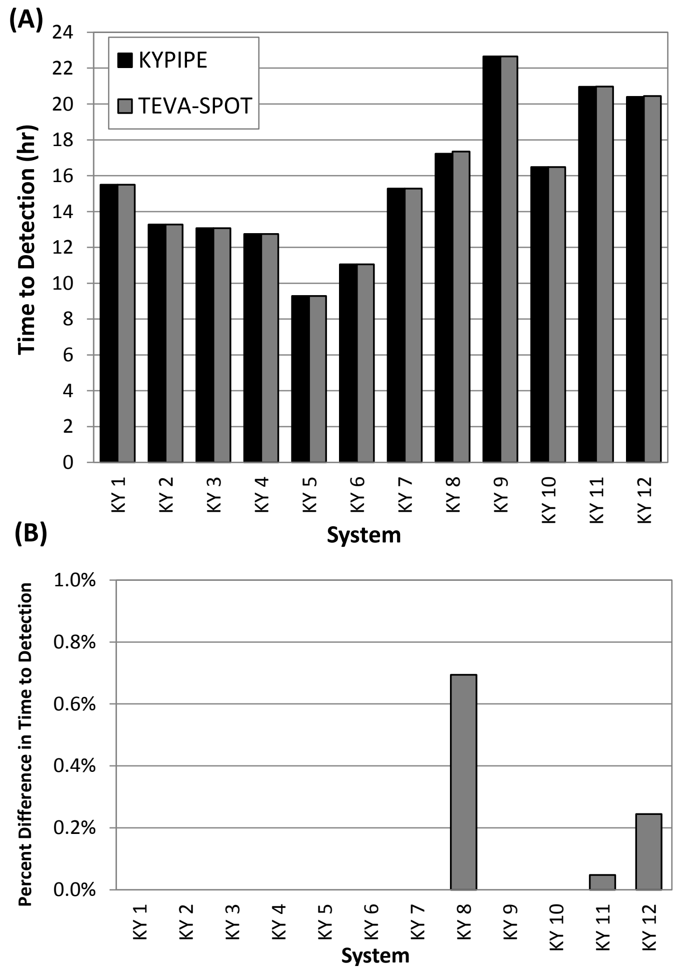


Figure 3.6: Comparison of Nodes Selected by KYPIPE and TEVA-SPOT for Baseline Conditions and Placement of One Sensor: (A) Comparison of Times to Detection; (B) Percent Difference in Times to Detection.

Figure 3.6 shows that sensors selected by KYPIPE for the baseline contamination scenario resulted in times to detection either equal to that of nodes selected by TEVA-SPOT or slightly lower for all system models. Similar results were found for all 15 of the contamination scenarios, thus confirming that the complete enumeration strategy employed by KYPIPE was either equal to or superior to the performance of the GRASP algorithm used by TEVA-SPOT. Similar results were obtained for the two sensor solutions as well. While the TEVA-SPOT algorithm generally required less computation time than KYPIPE, the differences in times were not that significant. The largest system (i.e. KY 12) illustrated the worst case scenario in terms of computation times for this study. This network required 45 minutes for KYPIPE and 13 minutes by TEVA-SPOT for the placement of one sensor. When placing two sensors, KYPIPE required 1 hour and

20 minutes while TEVA-SPOT used 13.5 minutes. Differences in computational times were not as significant for the remainder of systems in the model database.

As mentioned, it was found that the KYPIPE optimization method resulted in slightly lower or equal times to detection for all 15 contamination scenarios for all 12 systems. Although sensors selected by KYPIPE were always superior or equal to those chosen by TEVA-SPOT, the differences in average times to detection were minimal. The time to detection between the nodes selected by each program for the same system and contamination scenario were fairly similar (if not equal), as shown by the average percent difference (averaged over the 15 contamination scenarios) in time to detection for all 12 systems displayed in Figure 3.7. The average percent difference in times is relatively low for all systems. It should be noted that the few systems with 0 percent average time differences did not all have matching sensor selection for all 15 scenarios, but the time differences between the selected nodes in these cases were negligible.

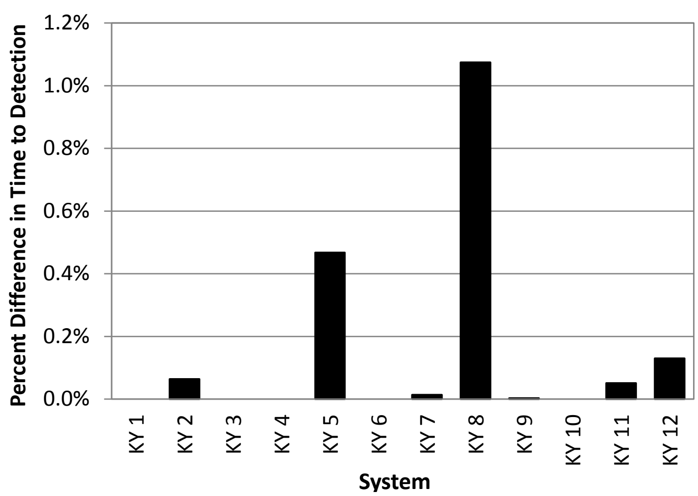


Figure 3.7: Average Percent Difference in Time to Detection between Nodes Selected by TEVA-SPOT and KYPIPE for Baseline Scenario and Placement of One Sensor.

In addition to comparing the times to detection for nodes selected by KYIPIPE and TEVA-SPOT, the times to detection obtained by KYIPIPE averaged over the contamination scenarios for both one and two sensor systems were also compared (see Figure 3.8). As can be seen from the figure, addition of a second sensor, at least for the 12 systems examined, did not seem to add a significant amount of benefit. All but three of the systems resulted in less than 15% percent decrease in average time to detection when the second sensor was added. Thus, for the small systems analyzed, one might argue that one sensor might be adequate. Additional analyses would be required to confirm such a hypothesis.

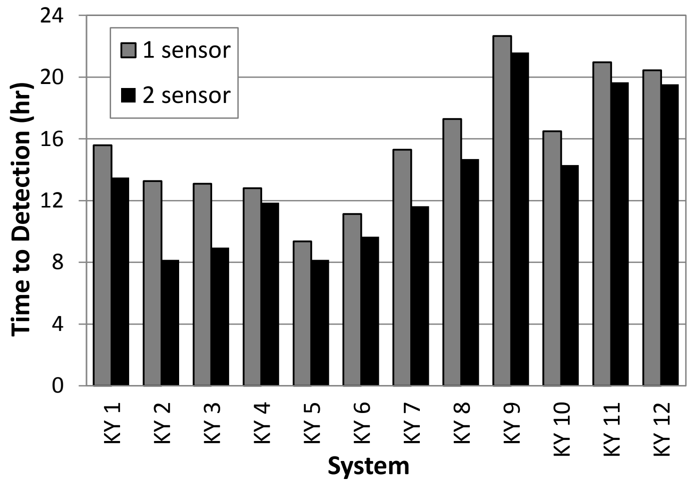


Figure 3.8: Comparison of Performance between the Placement of One and Two Sensors.

3.5.3 Comparison of Identical Sensor Placement

Along with a comparison of the times to detection of nodes selected by KYPIPE and TEVA-SPOT, the location of nodes chosen as optimal sensors locations by both programs were also compared. Some contamination scenarios for the same system resulted in TEVA-SPOT and KYPIPE selecting the same nodes as the optimal sensor locations. For each system model, the selected sensors for all 15 contamination scenarios were investigated. The percentage of the 15 contamination scenarios that resulted in identical sensor selection between KYPIPE and TEVA-SPOT are summarized in Figure 3.9 and Figure 3.10.

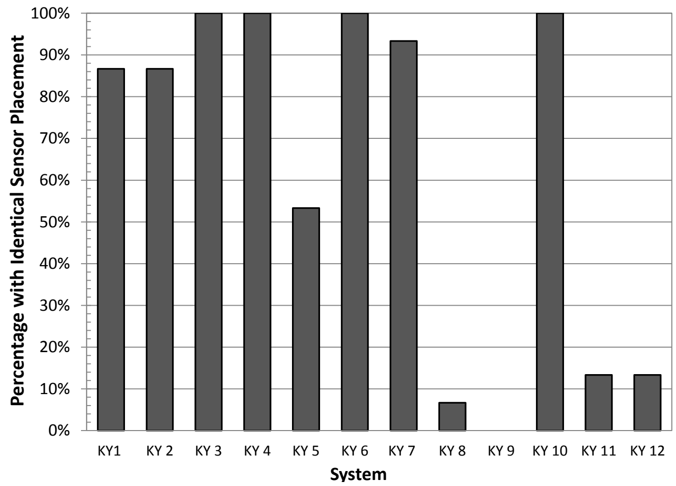


Figure 3.9: Percentage of Contamination Scenarios with Identical Sensor Selection between KYPIPE and TEVA-SPOT (1 sensor).

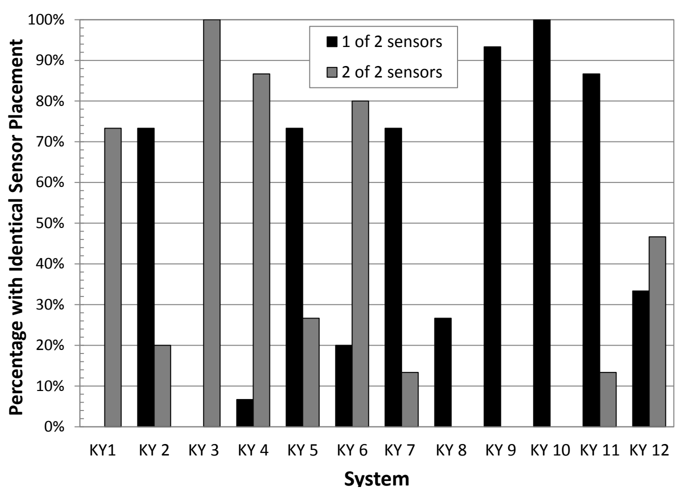


Figure 3.10: Percentage of Contamination Scenarios with Identical Sensor Selection between KYPIPE and TEVA-SPOT (2 sensors).

Figure 3.9 shows that some systems resulted in matching sensor selection between KYPIPE and TEVA-SPOT for all 15 contamination scenarios, while other networks did not have any matching sensor placement among scenarios. For the placement of one sensor, four of the 12 systems had matching optimal sensor nodes for all 15 scenarios, and eight of the 12 models had identical placement for over 50 percent of scenarios. On average, 9.4 out of the 15 scenarios (63 percent) resulted in identical placement of sensors for all systems. There were four systems that had less than 20% matching sensor nodes between KYPIPE and TEVA-SPOT, and one system (KY 9) did not have any matching sensor selection. In these systems with very few matching sensors, further investigation revealed that the vast majority of these sensors were still in very close proximity to each other. Only six contamination scenarios (out of the 15 scenarios performed on 12 systems for a total of 180 simulations) led to sensor locations that were considered to be far away from each other in the system, and all of these cases occurred in the KY 8 system. Although these few scenarios resulted in sensor selection that was considered to have significant spatial variation, the nodes were still located in the same general region of the system. This concept is shown in Figure 3.11. The top portion shows sensor selection that is considered to have significant spatial variation, and the bottom portion illustrates sensor selection in close proximity. As mentioned, the vast majority of scenarios with different sensor selection between KYPIPE and TEVA-SPOT resulted in nodes in very close proximity to each other for the placement of one sensor.

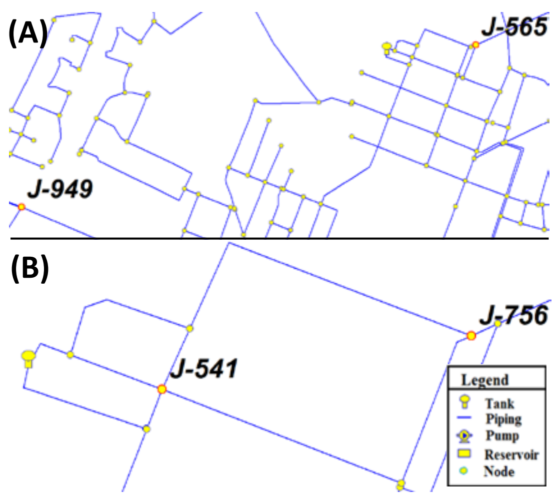


Figure 3.11: Spatial Variation in Sensor Selection (KY 8): (A) Significant Spatial Variation; (B) Close Proximity

Similar trends were present when placing two sensors as with the one sensor scenario. Figure 3.10 shows that some systems resulted in both sensors matching between KYPIPE and TEVA-SPOT for many of the 15 contamination scenarios, while other systems only matched one out of two sensors placed for certain scenarios. KY 3 was the only system to result in identical sensor placement for both sensors between KYPIPE and TEVA-SPOT for all 15 contamination scenarios. KY 1, KY 3, KY 4, and KY 6 resulted in two out of two matching sensor node selection for over 50 percent of the contamination scenarios, showing that KYPIPE and TEVA-SPOT produced very similar results in these systems. KY 8, KY 9, and KY 10 did not have any scenarios that matched both sensors, but these systems did have one out of two identical sensor nodes for several scenarios. KY 2, KY 5, KY 7, KY 9, KY 10, and KY 11 resulted in one out of two matching sensors for over 70 percent of the contamination scenarios. An average of 5.8 scenarios (38%) of the 15 contamination scenarios averaged over all systems resulted in matching sensor selection for both sensors, while 7.3 out of the 15 scenarios (49%) resulted in identical sensor placement for one of the two sensors, averaged over all 12 networks.

The cases where KYPIPE and TEVA-SPOT recommended different sensor nodes were investigated. As with the placement of one sensor, the vast majority of these cases resulted in placement of sensors that were in close proximity to each other. Only a few cases produced results where the sensors recommended by KYPIPE and TEVA-SPOT were significantly far away from each other. Specifically, 20 cases (out of the 15 simulations run on all 12 systems) led to sensor selection between the two programs that varied considerably spatially. In all of these cases, only one of the two sensors placed showed significant spatial variation between the two programs. In 18 of these cases, placement of the other sensor was identical, and the other two scenarios placed the remaining sensor in very close proximity. 15 of these 20 cases of significant spatial variation of one sensor occurred in KY 10, three were present in KY 6, and the final two cases occurred in KY 12.

Because several cases occurred where KYPIPE and TEVA-SPOT selected different sensor nodes, the ranking of the nodes chosen by TEVA-SPOT were investigated using the average times to detection for every possible sensor location generated by KYIPE. The data in Table 3.3 displays the percentage of the 15 contamination scenarios that resulted in differing sensor node selection between KYPIPE and TEVA-SPOT for the placement of one sensor (also shown in Figure 3.9). Table 3.3 also shows the ranking of the node selected by TEVA-SPOT (averaged over all 15 contamination scenarios) based on times to detection generated by KYPIPE, the total number of possible sensor locations, and the percentage of sensor locations with higher rankings (lower times to detection) than the location selected by TEVA. The values reported for average ranking of the node and percent of sensor locations with lower times to detect include cases where KYPIPE and TEVA-SPOT selected the same sensor.

Table 3.3: Ranking of Sensor Nodes Selected by TEVA-SPOT (1 sensor).

System	Possible Sensor Locations	Percentage of Scenarios Resulting in Different Sensor Selection	Average Ranking (by KYPIPE) of Node Selected by TEVA-SPOT	Average Percent of Sensor Locations with Lower Times to Detect
KY 1	509	13.3%	1.13	0.03%
KY 2	597	13.3%	1.13	0.02%
KY 3	224	0.0%	1.00	0.00%
KY 4	683	0.0%	1.00	0.00%
KY 5	305	46.7%	1.87	0.28%
KY 6	386	0.0%	1.00	0.00%
KY 7	378	6.7%	1.20	0.05%
KY 8	926	93.3%	7.27	0.68%
KY 9	836	100.0%	2.53	0.18%
KY 10	673	0.0%	1.00	0.00%
KY 11	547	86.7%	2.73	0.32%
KY 12	1908	86.7%	8.13	0.37%

If the node selected by TEVA-SPOT is ranked high (and thus the percent of sensor combinations with lower times to detection is low), this shows the results provided by the two programs are similar. Even when KYPIPE and TEVA-SPOT select different ideal sensor nodes, similar times to detection and high rankings of the node chosen by TEVA-SPOT show that both programs are effective in providing sensor locations that will be able to detect contaminants quickly. Table 3.3 shows that all systems averaged less than 1 percent of possible sensor combinations that are considered better than the sensor locations selected by TEVA-SPOT in terms of low time to detection. Even though KY 8 and KY 12 had slightly higher values for average ranking of the node selected by TEVA (7.27 and 8.13, respectively), they still had very low percentages of sensor locations with faster times to detection.

3.6 Analysis and Discussion

Results of the verification study demonstrate the effectiveness of the KYPIPE sensor placement optimization method for small systems. The slightly faster times to detection (as compared to nodes selected by TEVA-SPOT) for the non-common selected sensor locations using the KYPIPE algorithm show that KYPIPE is producing slightly superior sensor placement results to TEVA-SPOT (utilizing the GRASP heuristic method). However, the relatively low differences in average times to detection of the selected sensor nodes that did not match between the two programs show that results are very similar. The programs did select identical sensor locations in many cases, but the KYPIPE algorithm will always produce superior (or the same) sensor placement over TEVA-SPOT. The average percent difference in time to detection between nodes selected by TEVA-SPOT and KYPIPE for the placement of one sensor was 0.15%. This value takes into account the numerous scenarios where TEVA-SPOT and KYPIPE selected the same sensor node. The maximum percent difference in average time to detection between differing nodes selected by the two programs was 2.9 percent.

Because the models used in both TEVA-SPOT and KYPIPE software are uncalibrated models of real distribution systems, the hydraulic/water quality analyses and subsequent times to detection for all possible sensor locations are only estimates. However, the data should be fairly similar to results that would occur through tracer studies or other field testing. Because KYPIPE utilizes the EPANET engine to perform hydraulic/water quality analyses, the occasional slightly faster times to detection can be attributed to the optimization method utilized by KYPIPE, which will always produce superior or equal results. KYPIPE utilizes an enumeration method that calculates travel times for the entire solution space while a GRASP heuristic method was utilized in TEVA-SPOT for this study. Therefore, it is logical that the times between the programs are similar but KYPIPE consistently produces slightly faster times.

Both TEVA-SPOT and KYPIPE were used to locate either one or two water quality sensors for 12 different water distribution systems. Fifteen different contamination scenarios were evaluated for each system. The results of this analysis have provided the following conclusions:

1) The KYPIPE sensor placement tool provides sensor locations equal to or superior to those provided by TEVA-SPOT when using the GRASP optimization option along with an objective to minimize the time to detection.

2) The TEVA-SPOT algorithm was able to converge to a solution in less time than the KYPIPE sensor tool. The relative difference in computational times was greater for the

two sensor solutions than the one sensor solutions. Such an observation is to be expected given the fact that the KYPIPE sensor tool uses a complete enumeration algorithm. Despite this fact, the actual computational requirements for the KYPIPE sensor tool were not excessive, even for the largest system analyzed (i.e. KY 12 which had nearly 2000 potential sensor locations).

3) While the KYPIPE sensor placement tool was superior to the TEVA-SPOT algorithm, the results were generally not that significant. Thus, the GRASP algorithm used by TEVA-SPOT would appear to be fairly efficient, even providing the global optimal solution in 8 of the 12 systems analyzed (for the baseline contamination scenario when placing one sensor).

4) A comparison of the times to detection for both the placement of one and two sensors in the systems revealed that the average time to detect did not significantly decrease with the addition of a second sensor. Thus, for small systems, use of a single sensor might be adequate to provide an acceptable level of protection for utilities with limited financial resources. Additional analyses with an increased number of sensors should be performed to validate this hypothesis.

5) If one or two sensors will provide sufficient coverage for many small systems, some general rules or guidelines could be developed for sensor placement that might be able to avoid the requirement of a calibrated network model as currently required by TEVA-SPOT and KYPIPE. Possible such methodologies for single sensor systems have been proposed by Schal et al. (2013a & 2013b). Such methodologies could prove to be especially helpful for small utilities that may not have the technical or financial resources to employ computer model based approaches such as TEVA-SPOT.

CHAPTER 4

4 A Simplified Procedure for Sensor Placement Guidance for Small Utilities

4.1 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 & 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.

4.2 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.

4.2.1 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.

4.2.2 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.

4.2.3 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).

4.2.4 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 concentration 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 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).

4.3 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 (Aral et al., 2010). 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., 2013c). 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.

4.4 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.

4.4.1 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 of the system is in 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 of 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.

Loop 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 (Von Huben, 2005). Loop and grid 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 loop systems, the larger water lines (that convey the greatest flow) in grid 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. The water lines in grid systems are sometimes laid out to resemble a checkerboard (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 4.1.

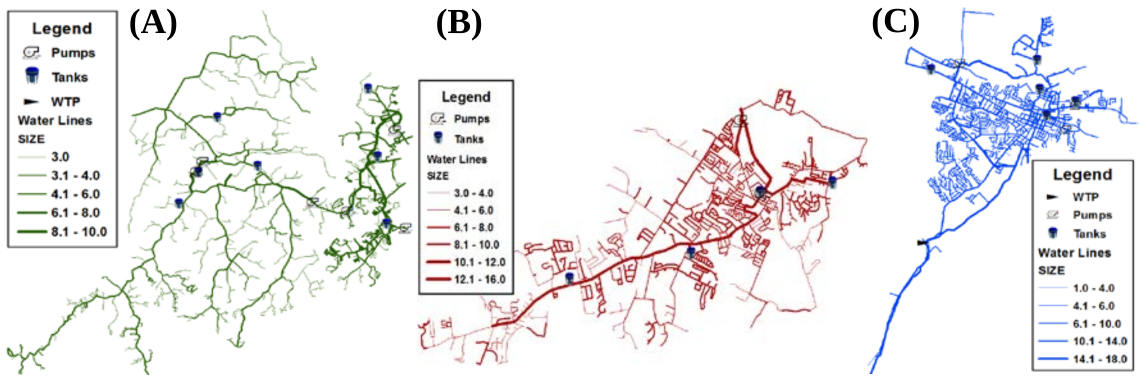


Figure 4.1: System Configurations: (A) Branch; (B) Loop; (C) Grid.

4.4.2 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 loop systems is shown in Figure 4.2

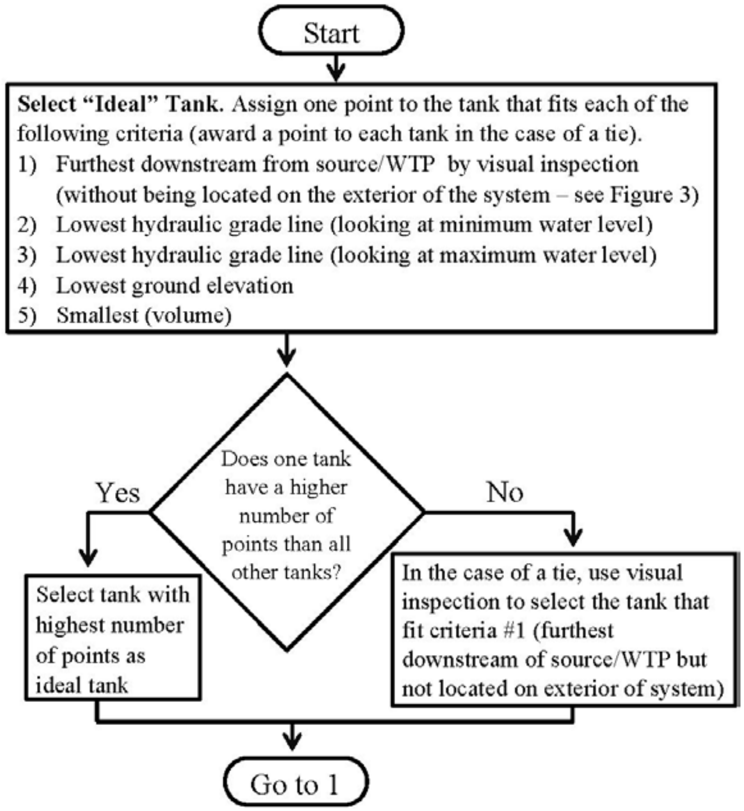


Figure 4.2: Ideal Tank Selection (Loop Systems).

Figure 4.3 displays examples of tanks considered exterior, which can serve as a tool in the tank selection step.

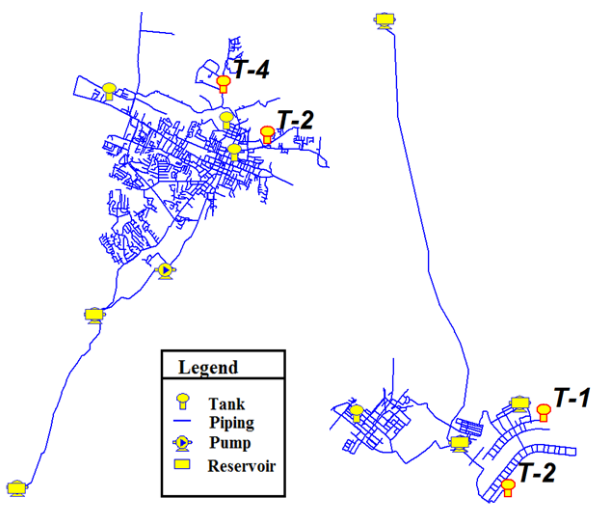


Figure 4.3: Examples of Exterior Tanks.

The procedure for selection of the ideal tank in grid systems is shown in Figure 4.4. If the system has five or more tanks, a preliminary step is necessary in selecting the ideal tank.

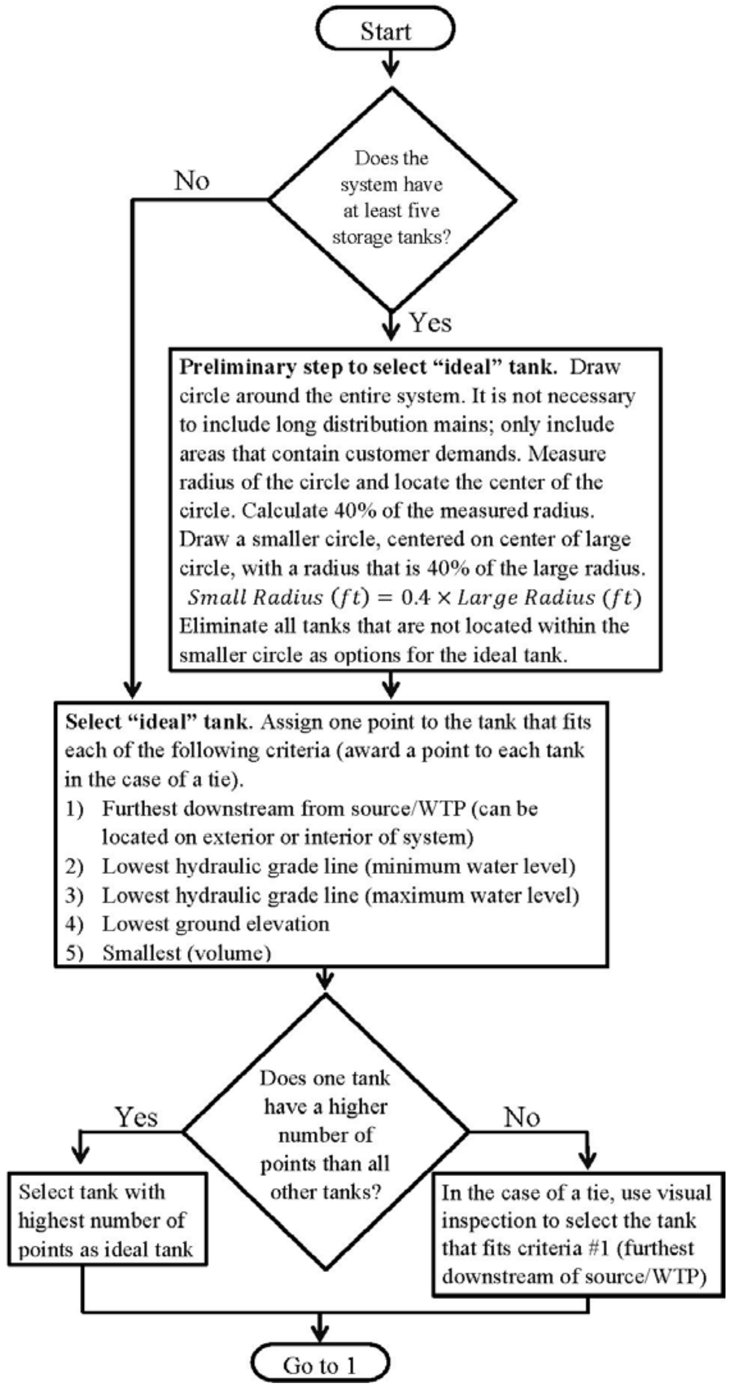


Figure 4.4: Ideal Tank Selection (Grid Systems).

The process for ideal tank selection in branch systems is slightly more complex and requires several steps, shown in Figure 4.5. 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 the 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 4.6 shows an example of a system with an easily distinguishable downtown area, which can serve as a tool in the tank selection step.

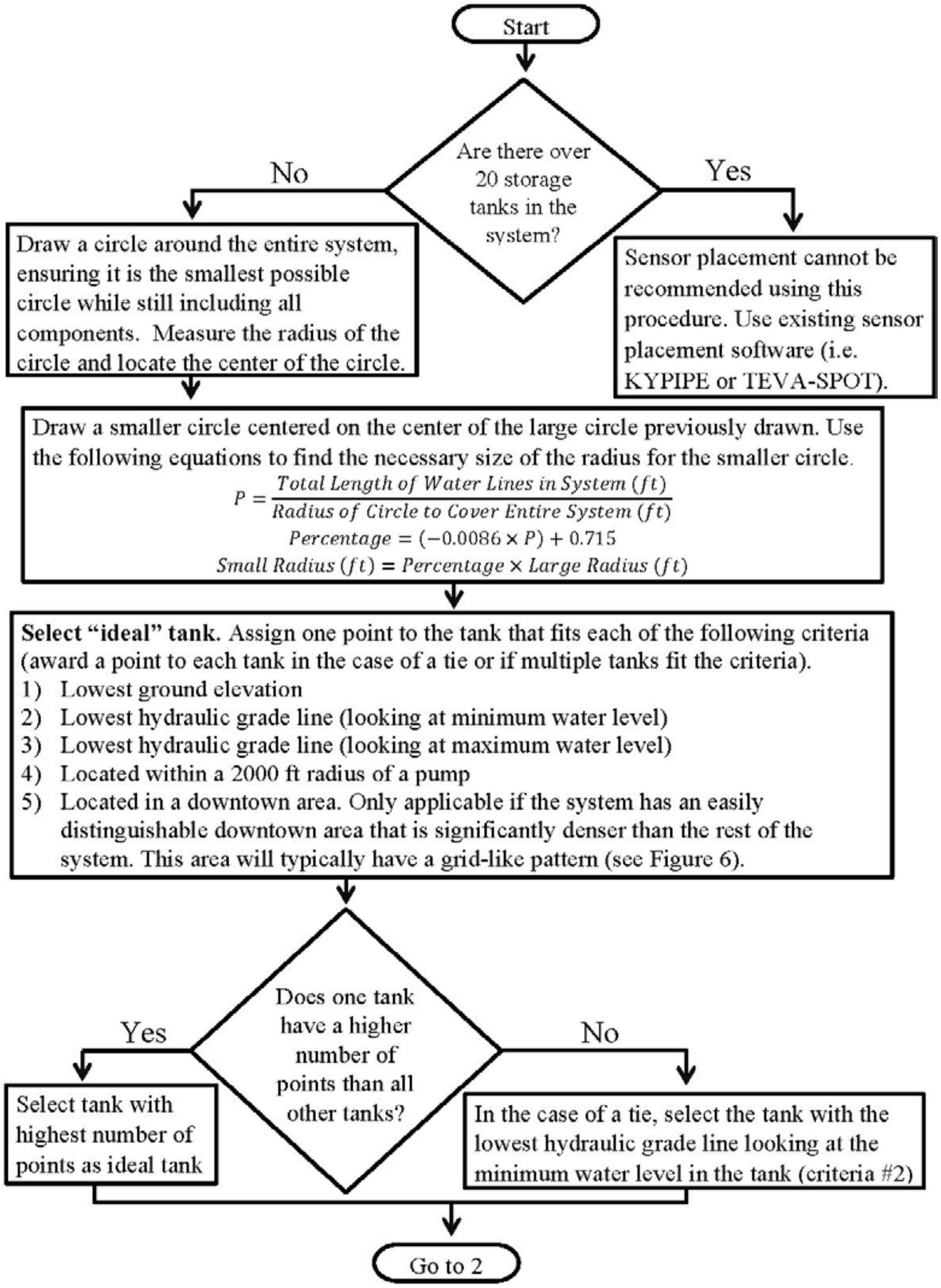


Figure 4.5: Ideal Tank Selection (Branch Systems).

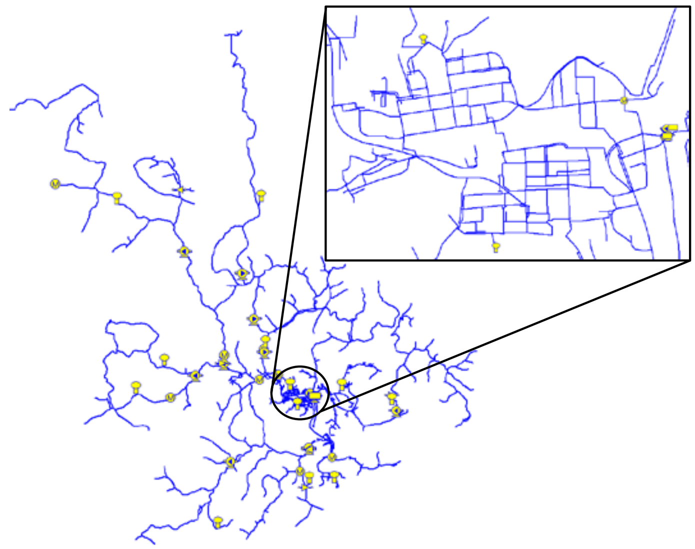


Figure 4.6: Example of Downtown Area (Branch Systems).

4.4.3 Draw a Circle Around the Ideal Tank

The third main step of the procedure draws 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 4.7.

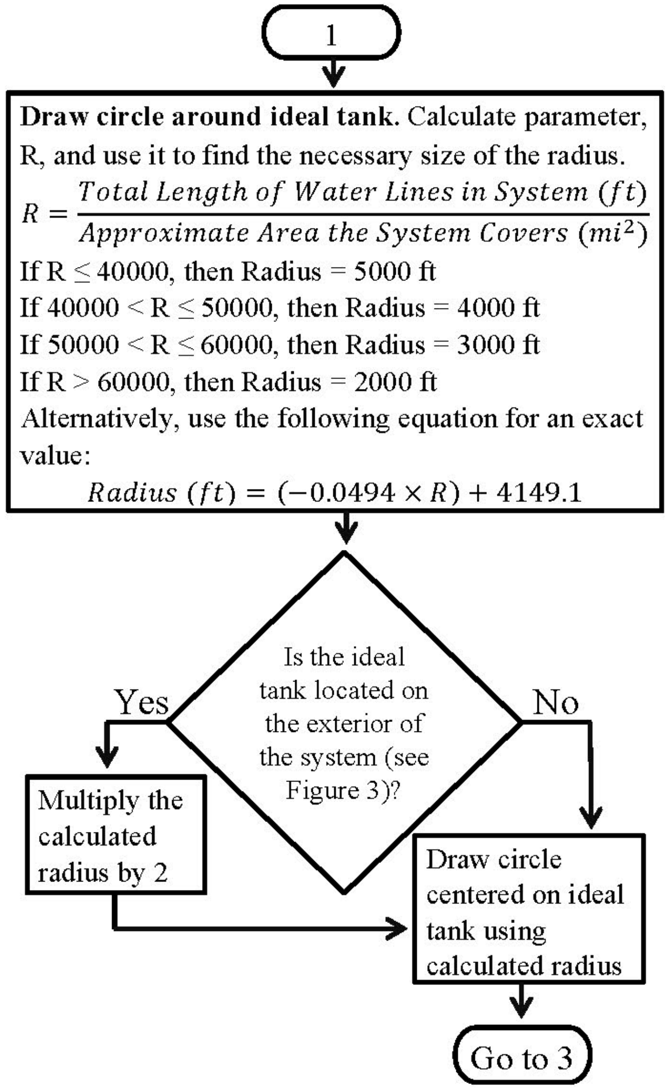


Figure 4.7: Circle Around Ideal Tank (Loop and Grid Systems).

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 4.8.

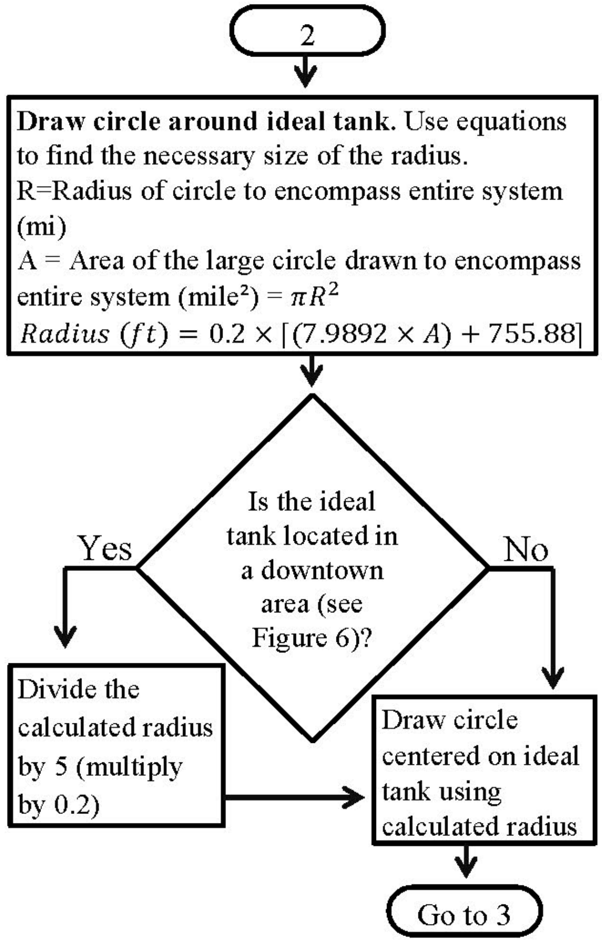


Figure 4.8: Circle Around ideal Tank (Branch).

4.4.4 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 4.9.

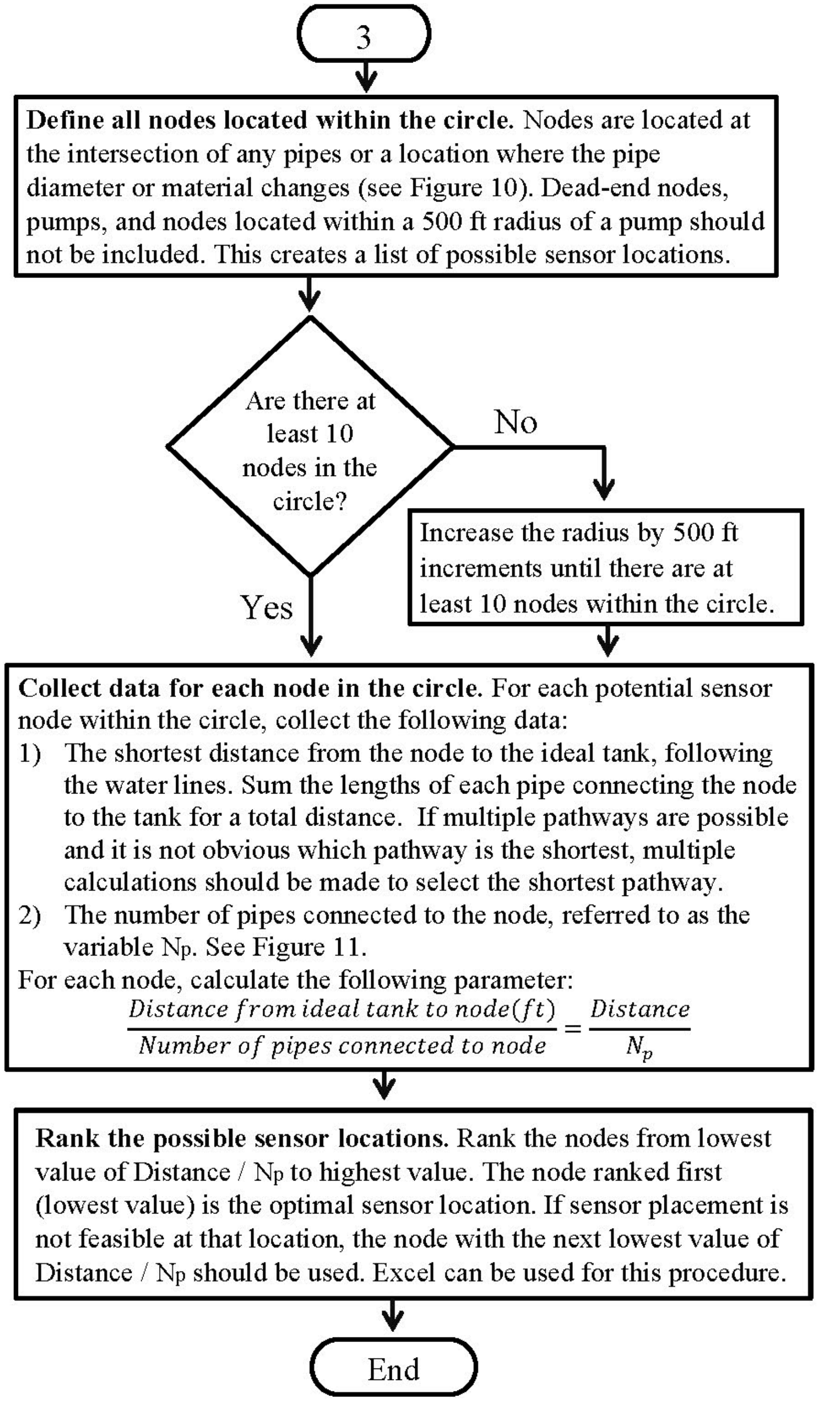


Figure 4.9: Final Steps (All Systems).

Figure 4.10 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.

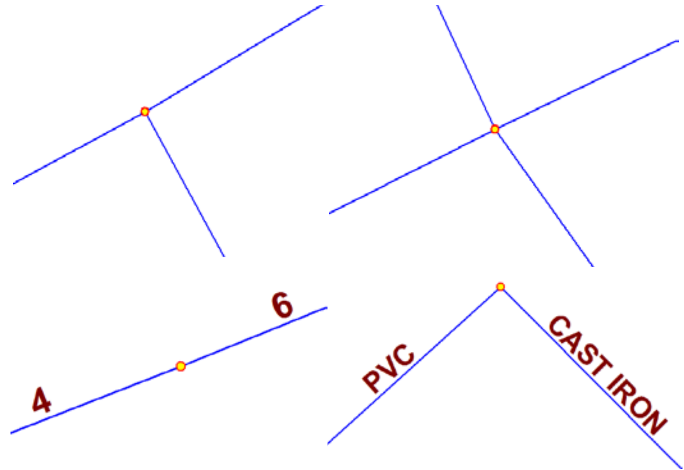


Figure 4.10: Examples of Nodes.

Figure 4.11 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.

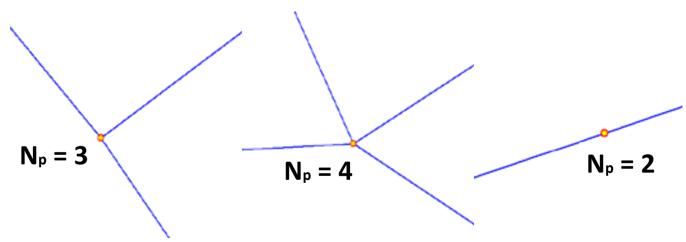


Figure 4.11: Examples of the Variable N_p.

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 4.12. 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 4.12 is considered the optimal location.

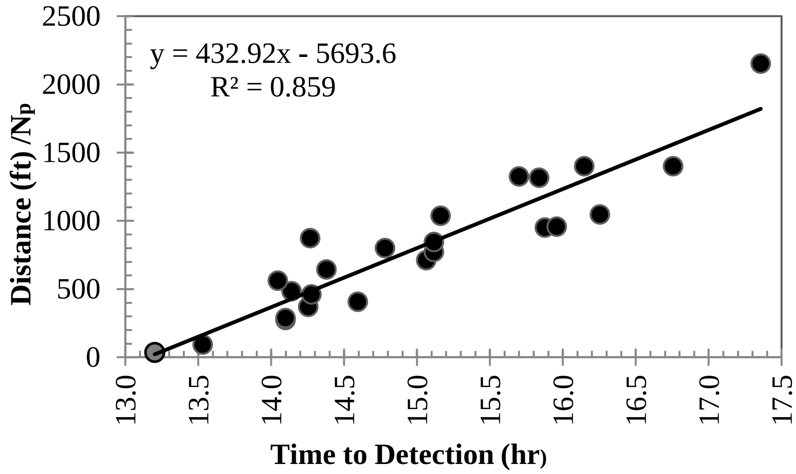


Figure 4.12: Distance/ N_p vs. Time to Detection for System Nodes (KY 3).

4.5 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 loop, grid, 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 4.1 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 4.1: Comparison of Sensor Selection between KYPIPE and Procedure.

System	Possible Sensor Nodes	KYPIPE		Simplified Procedure			Time Difference (hr)	Percent Difference in Times
		Selected Node	Time to Detect (hr)	Selected Node	Time to Detect (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 loop configured systems, 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 loop system was able to select the most ideal node using the guidance procedure.

The procedure tested on the grid 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 4.13 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 grid systems.

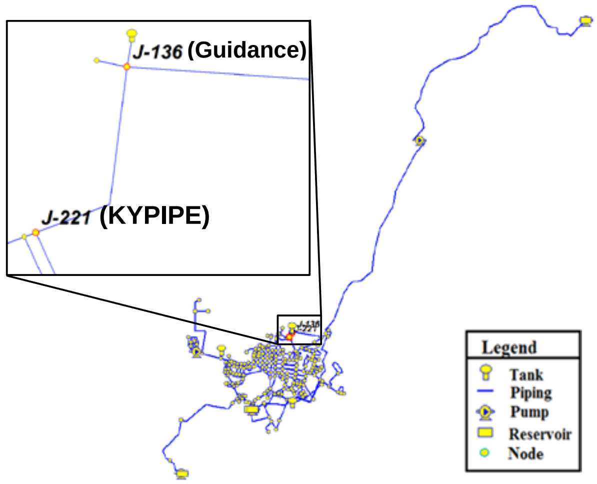


Figure 4.13: **Sensor Locations Comparison (KY 14).**

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 4.14.

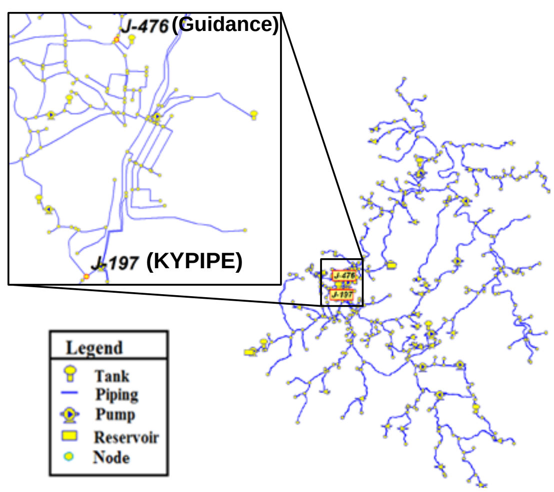


Figure 4.14: **Sensor Locations Comparison (KY 15).**

When looking at the entirety of the system in Figure 4.14, 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.

The full sensor placement guidance procedure is outlined in Appendix B, including additional figures to aid in understanding of the procedure and an example of the procedure executed on a system in each configuration. Appendix C shows the procedure executed on the verification systems, and Appendix D includes all data used in development of the guidance procedure.

CHAPTER 5

5 A Graphical Procedure for Sensor Placement Guidance for Small Utilities

5.1 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., 2013c). 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 Chang et al. (2012a) 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., 2013c) 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.

5.2 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 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 #". Identifying information, such as the pumps and tank name for the actual systems represented by the models, was removed for security purposes. All system models used in this study were 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.

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, creating the “loop parameter”, for the five systems in the loop configuration. Similar relationships were developed for the branch and grid configurations, resulting in the “grid parameter” and “branch parameter”. 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 shown in Figure 1. In the figure, the data points used to develop the exponential trend (blue circles) along with the verification system (red square) are shown. In the plots, alpha (α) serves as a scaling factor and α equals 0.001.

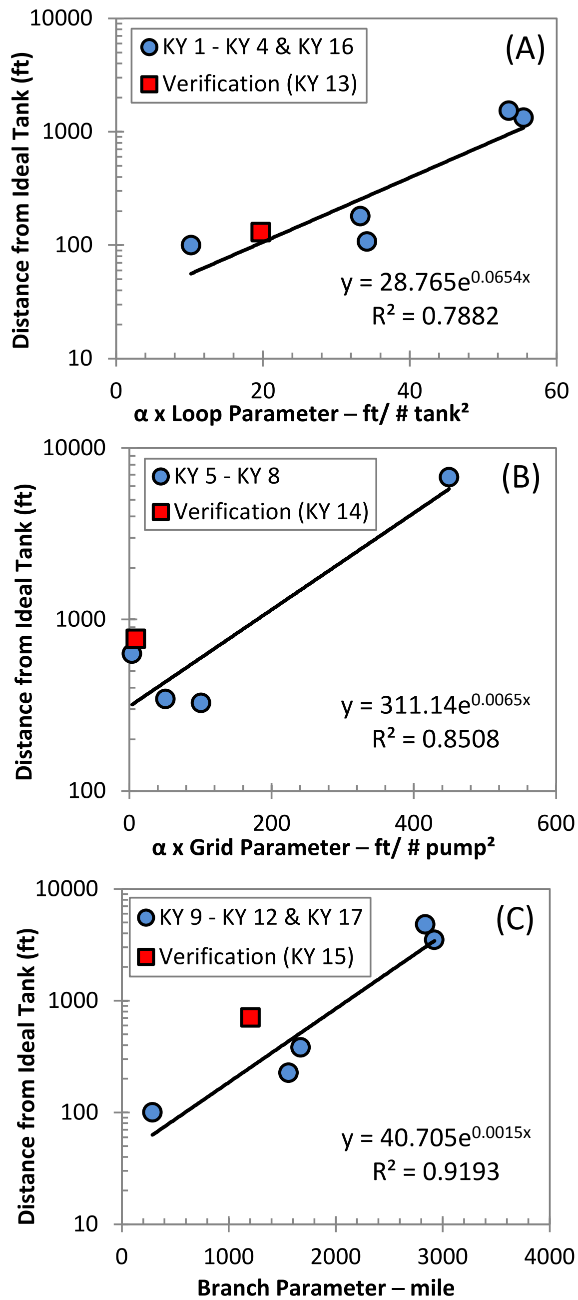


Figure 5.1: Development of Regression Equations: (A) Loop; (B) Grid; (C) Branch.

5.3 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, developed 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. To calculate the grid and loop parameter, 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 the branch parameter, 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 5.2 may be used as a general visual guide to determine which configuration best describes a particular water distribution system.

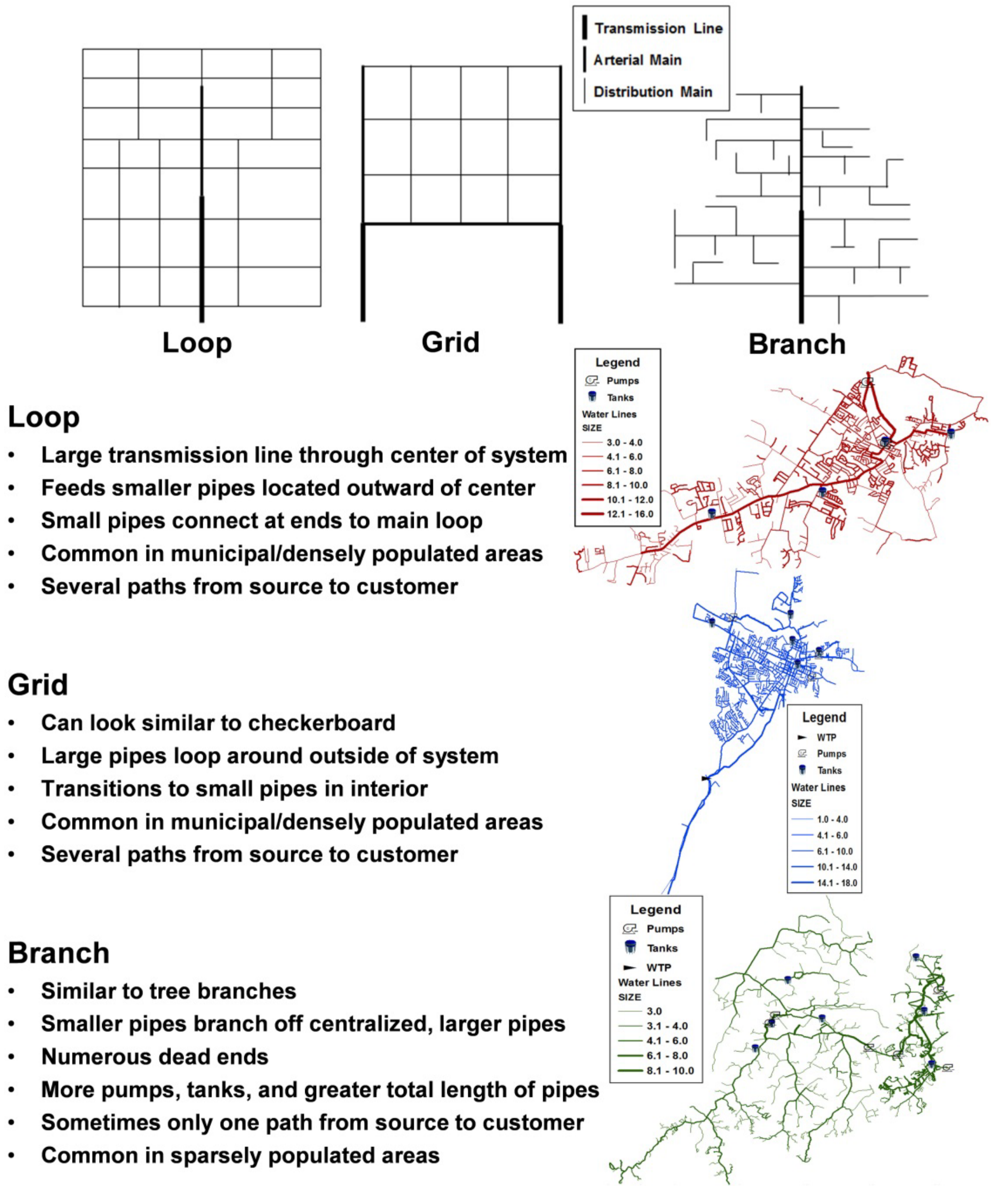


Figure 5.2: Determining Water Distribution System Configuration.

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 5.3.

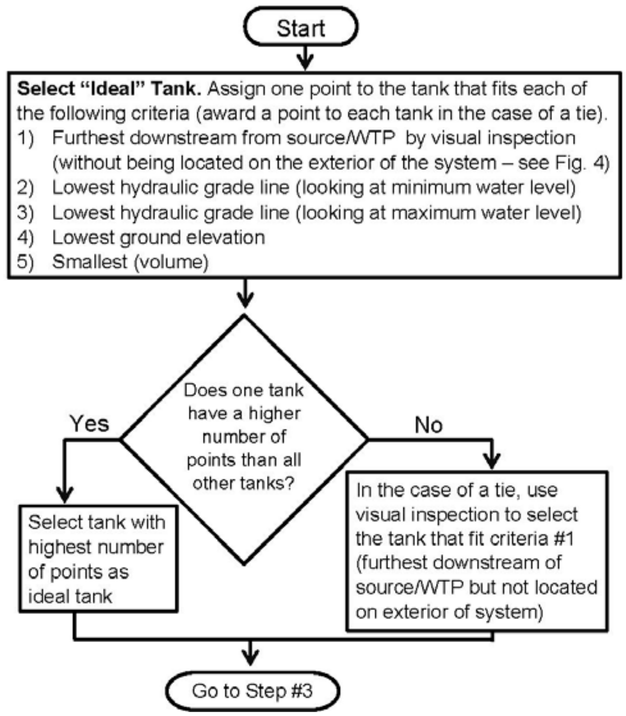


Figure 5.3: Step 2: Ideal Tank Selection (Loop Systems).

Figure 5.4 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.

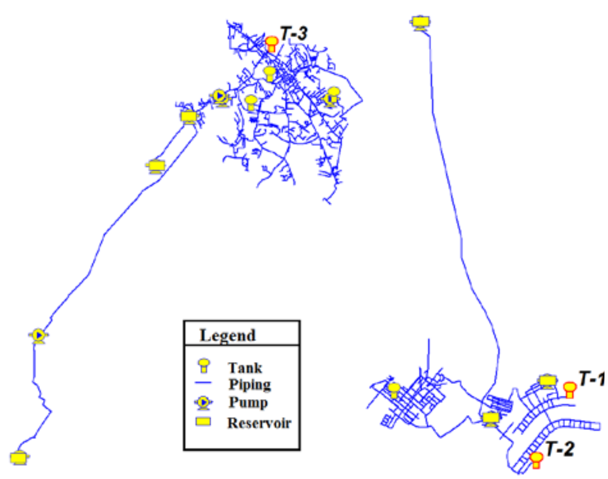


Figure 5.4: Examples of Exterior Tanks.

The procedure for selection of the ideal tank in grid systems is shown in Figure 5.5. If the system has five or more tanks, a preliminary step is necessary in selecting the ideal tank.

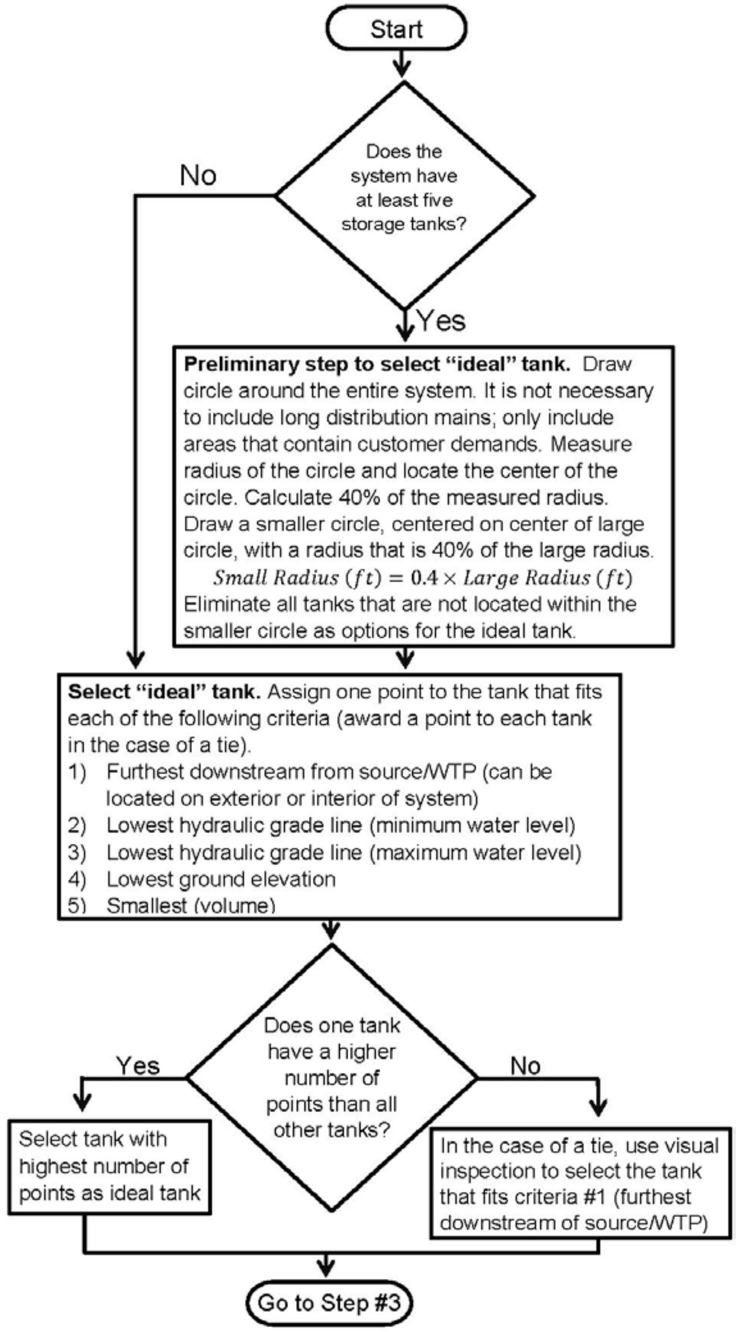


Figure 5.5: Step 2: Ideal Tank Selection (Grid Systems).

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 5.6. 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 5.7 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.

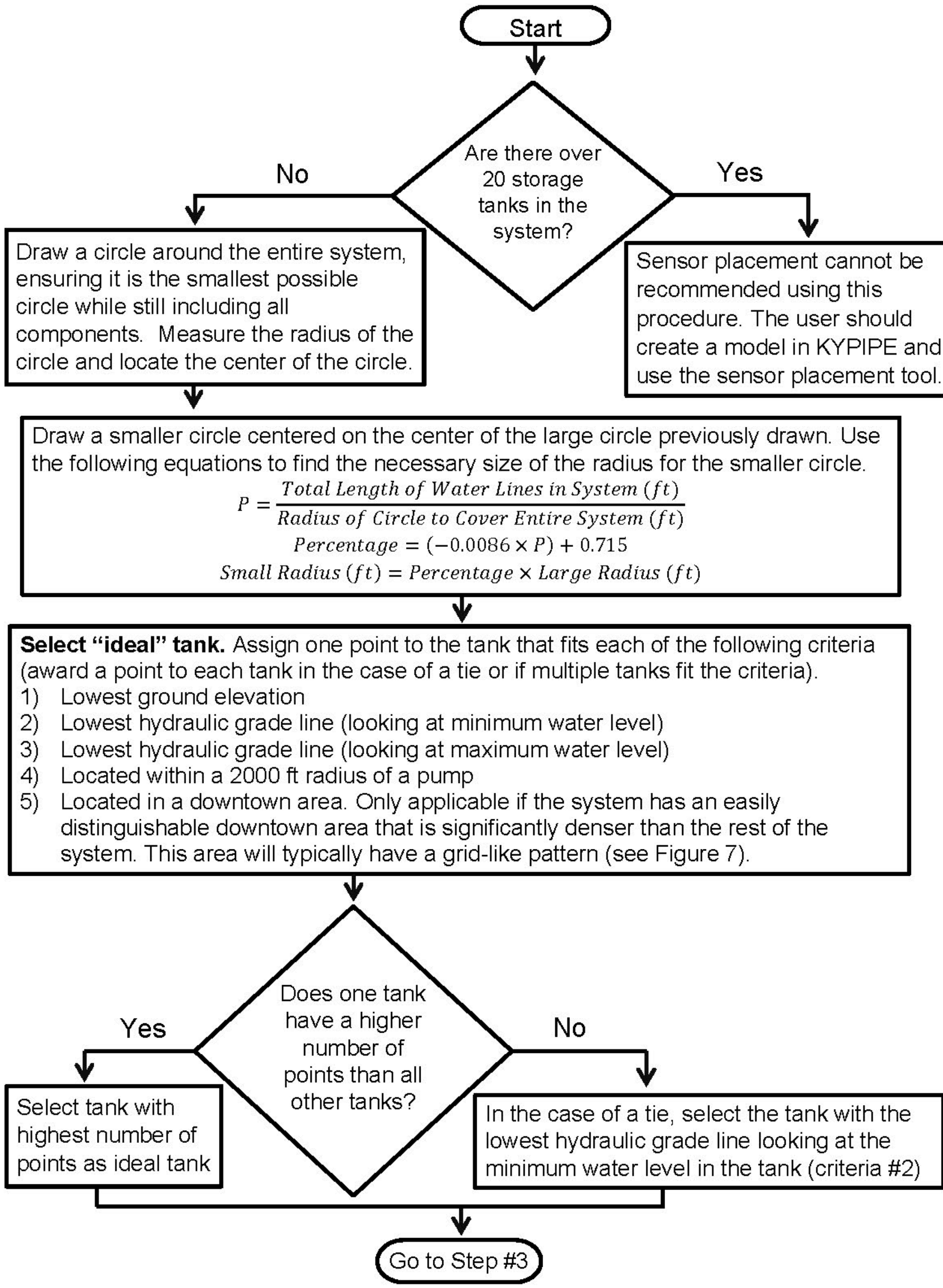


Figure 5.6: Step 2: Ideal Tank Selection (Branch Systems).

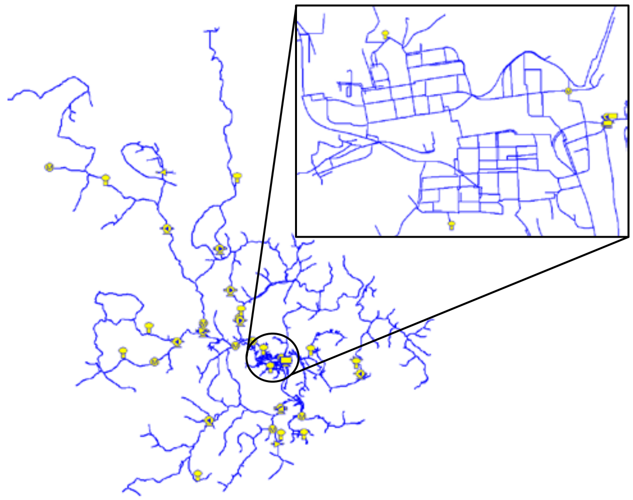


Figure 5.7: Example of Downtown Area (Branch).

Step 3: Determine the recommended distance from ideal tank. The last step of the graphical 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 5.8, and Figure 5.9 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 5.10 illustrates this concept. The ideal tank and the diameters of water lines are labeled; the correct pathway that should be followed is marked by arrows and highlighted in red. In the top portion of Figure 5.10, 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.

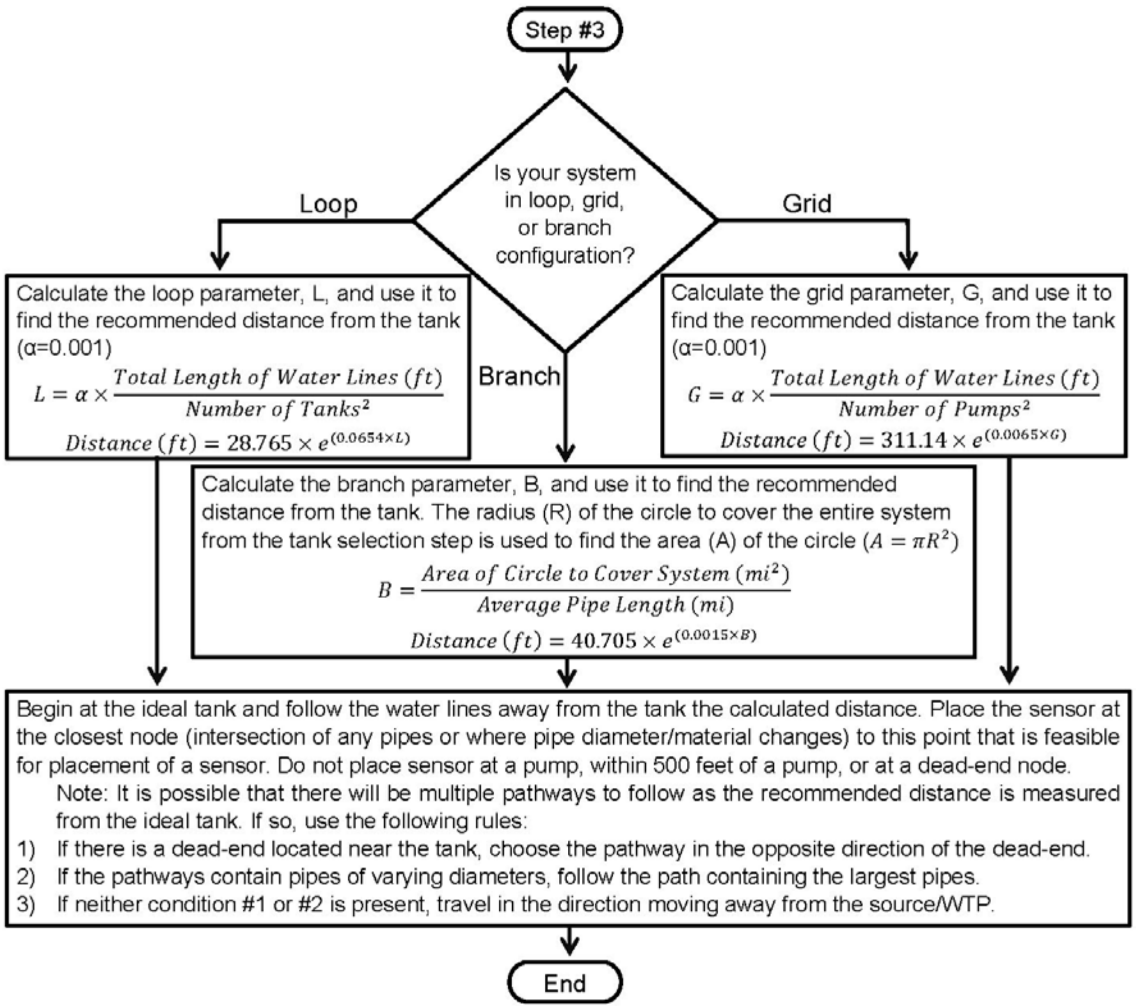


Figure 5.8: Step 3 of Graphical Procedure (All Systems).

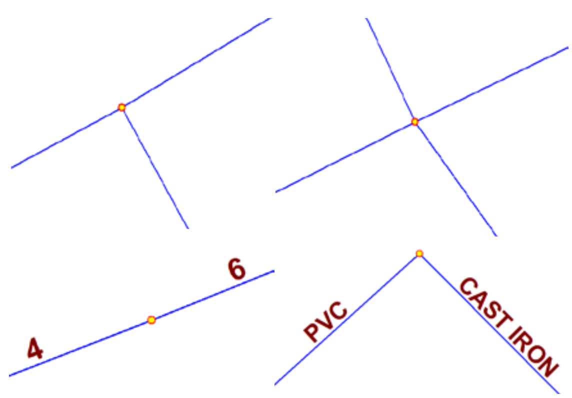


Figure 5.9: Examples of Nodes.

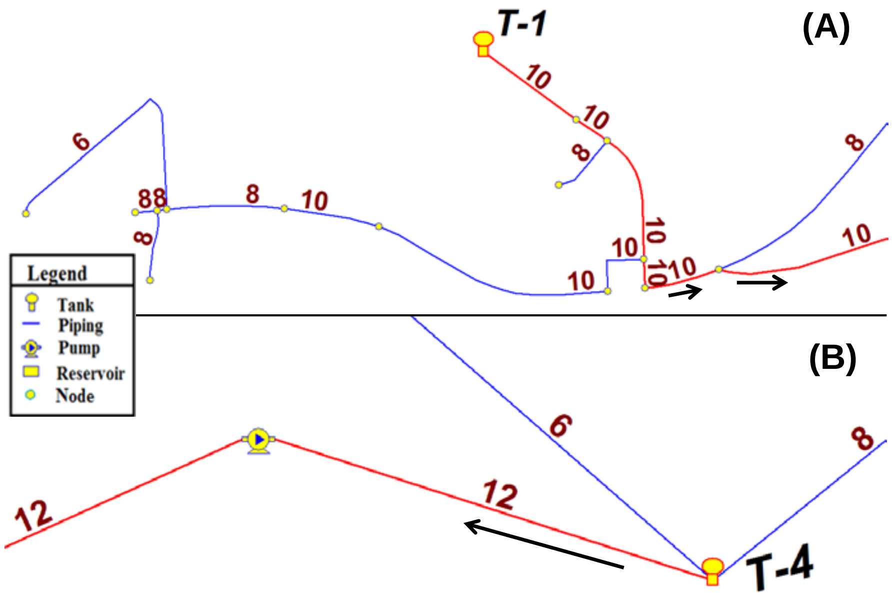


Figure 5.10: Selection of Pathway from Ideal Tank: (A) KY 7; (B) KY 1.

5.4 Illustration of the Methodology

An illustration of the methodology for a loop system (i.e. KY 1 in Figure 5.11) is provided below. Figure 5.11 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 5.1 shows data for all tanks in the system, including the total number of points each tank was awarded in step #1.

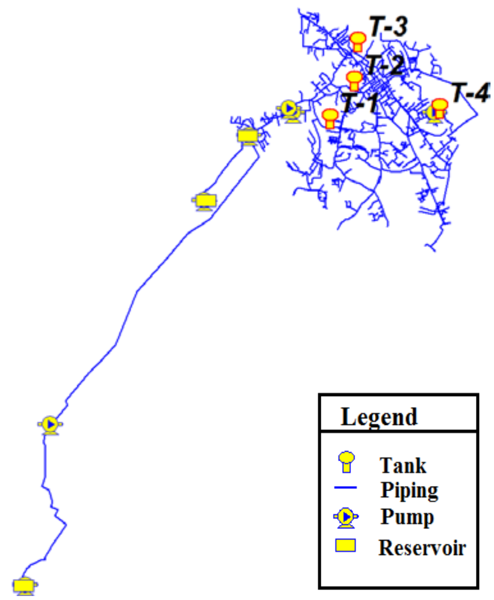


Figure 5.11: Example of Ideal Tank Selection (KY 1).

1) Furthest downstream of source/WTP without being located on exterior of system: T-4. Visual inspection of Figure 5.11was 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 5.1: 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?	Point Total
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 loop parameter, given as L, was calculated using the equation specified in Figure 5.8 for loop systems (shown below in Equation 5-1). In this equation, α = 0.001.

$$L = \alpha\left(\frac{Total\ Length\ of\ Water\ Lines\ in\ System\ (ft)}{Number\ of\ Tanks^2}\right) = 0.001\left(\frac{499535\ ft}{3^2}\right) = 55.50 \quad (5\text{-}1)$$

The parameter, L, was then used in Equation 5-2 to find the recommended distance from the tank.

$$Distance\ (ft) = 28.765 \times e^{(0.0654 \times 55.50)} = 1084.48\ ft \quad (5\text{-}2)$$

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 5.12, 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).

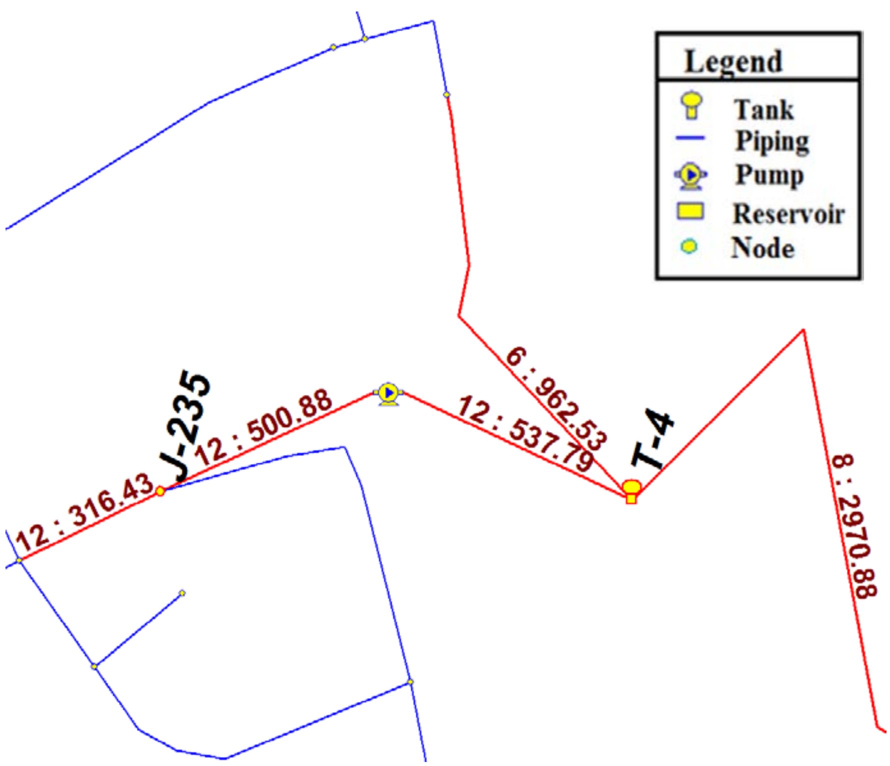


Figure 5.12: Example of Selecting Sensor Node (KY 1).

5.5 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 5.2 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 5.2: Sensor Selection using KYPIPE and Graphical Procedure.

System	Possible Sensor Nodes	KYPIPE		Graphical Procedure			Time Difference (hr)	Percent Difference in Times
		Selected Node	Time to Detect (hr)	Selected Node	Time to Detect (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 5.13.

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 5.13.

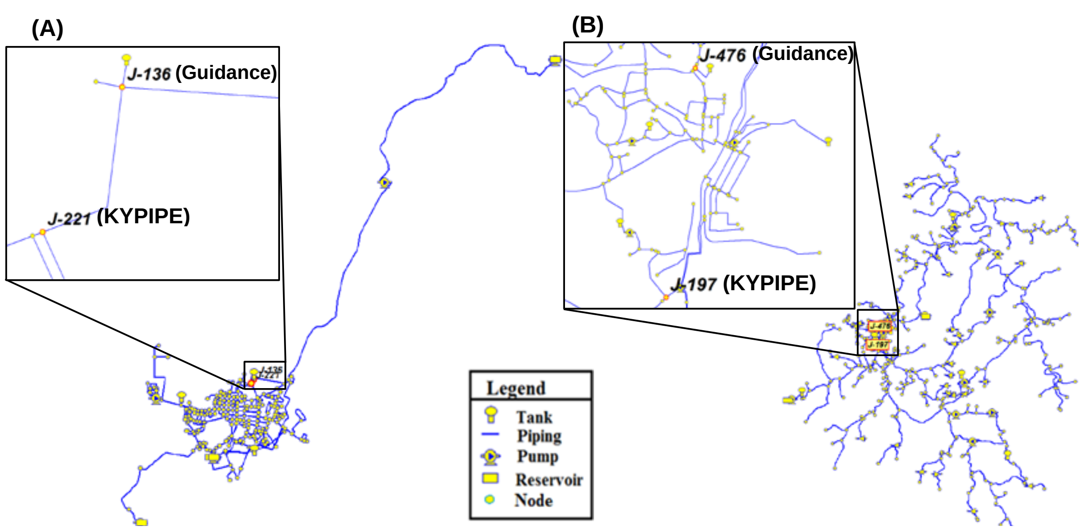


Figure 5.13: **Sensor Location Comparison: (A) KY 14; (B) KY 15.**

The accuracy of the simple procedure for sensor placement can also be evaluated by examining the plots in Figure 5.1. 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.

5.6 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 5.13. 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.

The full sensor placement guidance procedure is outlined in Appendix B, including additional figures to aid in understanding of the procedure and an example of the procedure executed on a system in each configuration. Appendix C shows the procedure executed on the verification systems, and Appendix D includes all data used in development of the guidance procedure.

CHAPTER 6

6 Conclusions

6.1 Statistical Analysis of Water Distribution Systems Conclusion

This report has outlined a database of 15 water distribution systems models that reflect actual distribution systems in Kentucky. This database of real networks can provide researchers a robust database for testing new algorithms for various network issues. The database is being provided free to the research community (via a dropbox) with models available in both KYPIPE and EPANET formats. Access to the dropbox may be granted by emailing the authors at wds@engr.uky.edu.

The models in the database were further investigated to determine if certain system characteristics varied systematically by configuration. Statistically significant differences in certain system parameters were found between loop and branch systems, along with grid and branch systems. These differences are not only useful for classification of systems into a configuration and improving understanding of how different systems operate, they can also be helpful with research relating to water security. This research was developed for future use in research relating to water quality sensor placement in distribution systems.

6.2 Sensor Placement Guidance for Small Utilities Conclusion

TEVA-SPOT has been developed to analyze the vulnerability of drinking water distribution networks to contamination and recommend locations to deploy water quality sensors as a component of contamination warning systems. However, the software may not be appropriate for small utilities in terms of the simplicity and ease of use. A water quality sensor placement tool was developed with KYPIPE to accomplish the objective of providing a simple tool to aid small utilities in the placement of sensors. The KYPIPE tool uses a complete enumeration optimization scheme along with EPANET for both hydraulic and water quality analysis. Both TEVA-SPOT and KYPIPE were used to locate either one or two water quality sensors for 12 different water distribution systems. Fifteen different contamination scenarios were evaluated for each system.

The KYPIPE sensor placement tool provides sensor locations equal to or superior to those provided by TEVA-SPOT when using the GRASP optimization option and an objective to minimize the time to detection. KYPIPE utilizes an enumeration method that calculates travel times for the entire solution space, which will always produce superior results. However, the TEVA-SPOT algorithm was able to converge to a solution in less time than the KYPIPE sensor tool. Although the KYPIPE sensor placement method was superior to the TEVA-SPOT algorithm, the results were generally not that significant. The high percentage of scenarios where both methods selected identical sensor nodes along with low differences in time to detection for non-common sensor selection demonstrates that the GRASP algorithm used by TEVA-SPOT is fairly efficient.

A comparison of the average times to detection for the placement of one and two sensors in the networks revealed that the average time to detect did not significantly decrease with the addition of a second sensor, so deployment of only one water quality sensor in a small system may be sufficient. If a small number of sensors will provide sufficient coverage for small systems, some general guidelines could be developed for sensor placement that might not require the use of a calibrated network model.

6.3 A Simplified Procedure for Sensor Placement Guidance Conclusion

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.

6.4 A Graphical Procedure for Sensor Placement Guidance Conclusion

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 instead 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.

6.5 Future Research

Future work in this area should expand sensor placement guidance to increase the number of sensors placed in the network. It was found that the majority of the nodes with the fastest times to detection were clustered in each system (for the placement of one sensor). Preliminary observation of the results from KYPIPE for the placement of two sensors showed that the sets of nodes with the fastest average times to detection were also clustered. A similar procedure could be developed for the placement of two or three sensors utilizing the geometry of the system. Providing guidance to place multiple sensors in a small water distribution system would improve the objective function for utilities with the resources to place multiple sensors.

Further research on this subject should also investigate the impacts of other objective functions such as the percentage of contamination events detected or the length of pipe contaminated. It has been debated which objective function should be used to generate the most effective sensor network design. It is likely that a combination of objective functions would provide the optimal balance of fast detection along with the ability to detect contamination from all parts of the system and provide the greatest protection of the population. Multiple objective functions could be considered in the evaluation of the current sensor placement guidance procedure, and multiple objectives could also be used to develop further sensor placement guidance for the placement of multiple sensors.

Appendix A

Statistical Testing on Water Distribution Systems

In this study, five water distribution system models were created for each of the three configurations. Various system parameters were investigated to determine if there were relationships present between various system parameters and the general system configuration (i.e. loop, grid, or branch). This investigation is outlined in Chapter 2. This appendix acts as supplementary information to Chapter 2 and includes all data used in statistical testing.

Table A.1 shows system parameters that were used in the investigation (also shown in Table 2.3). These values shown for each system configuration are averaged over the five systems classified into each configuration.

Table A.1: Average System Parameters.

System Parameter	Loop	Grid	Branch
Number of Tanks	3.8	3.4	14.2
Number of Pumps	3.8	4.6	16.6
Number of Nodes	704.6	604.6	1153
Total Length of Pipes (miles)	102.08	87.98	370.58
Average Length of Pipes (ft)	659.53	661.14	1787.23
Average Pipe Diameter (in)	7.516	8.651	5.227
Average Pipes/Node	1.212	1.222	1.082
Total System Demand (MGD)	1.896	1.776	1.694
Range of Elevations (ft)	228.7	262.7	622.3

Table A.2 shows the parameters normalized by the system demand (also shown in Table 2.4). To calculate these values, each parameter for every system was divided by the total system demand (MGD) for that particular system, and then these normalized values were again averaged for each configuration. It should be noted that the total system demand is included in this and subsequent tables, but these values were not normalized. Even though all parameters were normalized by system demand, they are included in the investigation to verify that the systems did not have statistically significant variance in total system demand.

Table A.2: Average System Parameters Normalized by System Demand.

System Parameter	Loop	Grid	Branch
Number of Tanks	2.1	2.0	8.3
Number of Pumps	2.1	2.7	10.3
Number of Nodes	394.9	334.7	742.5
Total Length of Pipes (miles)	57.9	51.1	237.7
Average Length of Pipes (ft)	362.9	419.1	1112.3
Average Pipe Diameter (in)	4.065	5.498	3.159
Average Pipes/Node	0.657	0.773	0.662
Total System Demand (MGD)	1.896	1.776	1.694
Range of Elevations (ft)	128.774	160.481	381.430

To determine if significant differences existed in these parameters based on system configuration, a series of one-tailed two-sample t-tests at the alpha = 0.05 significance level were performed. Three tests were performed for each system parameter. The first tested the difference between the loop and grid systems, the second investigated the difference between the loop and branch systems, and the last examined differences in the grid and branch networks.

As described in Chapter 2, the alternative hypotheses were determined by observing the means of the system parameters and hypothesizing that the configuration with the higher average value of the system parameter in question had the higher population mean in the alternative hypothesis. The null hypothesis (H_o) states that the means (μ) of the two populations are equal (H_o: $\mu_1 = \mu_2$), and the alternative hypothesis (H_a) states that one of the population means are higher (H_a: $\mu_1 > \mu_2$ or H_a: $\mu_1 < \mu_2$). Table A.3 displays the alternative hypotheses used in this study (also shown in Table 2.5).

Table A.3: Alternative Hypotheses for t-tests.

System Parameter	$Loop_1$ & $Grid_2$	$Loop_1$ & $Branch_2$	$Grid_1$ & $Branch_2$
Number of Tanks	$\mu_1 > \mu_2$	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$
Number of Pumps	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$
Number of Nodes	$\mu_1 > \mu_2$	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$
Total Length of Pipes (miles)	$\mu_1 > \mu_2$	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$
Average Length of Pipes (ft)	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$
Average Pipe Diameter (in)	$\mu_1 < \mu_2$	$\mu_1 > \mu_2$	$\mu_1 > \mu_2$
Average Pipes/Node	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$	$\mu_1 > \mu_2$
Total System Demand (MGD)	$\mu_1 > \mu_2$	$\mu_1 > \mu_2$	$\mu_1 > \mu_2$
Range of Elevations (ft)	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$	$\mu_1 < \mu_2$

The population variances were not assumed to be equal, so Equation A-1 was used to calculate the t value (Dielman, 2005).

$$t = \frac{\overline{y_1} - \overline{y_2}}{\sqrt{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)}} \tag{A-1}$$

where $\bar{y}$ is the mean of the sample, s represents the standard deviation of the sample, and n is the number of data points in the sample. The value for n was five for all cases because there were five systems for each system configuration. In order to calculate the t value, the standard deviations of the averaged values shown in Table A.2 were needed. These values are displayed in Table A.4.

Table A.4: Standard Deviation of Normalized System Parameters.

System Parameter	Loop	Grid	Branch
Number of Tanks	0.6	0.6	4.2
Number of Pumps	1.6	2.1	3.3
Number of Nodes	191.6	121.0	545.4
Total Length of Pipes (miles)	31.4	14.9	127.6
Average Length of Pipes (ft)	118.8	179.5	551.6
Average Pipe Diameter (in)	0.9	2.7	0.4
Average Pipes/Node	0.1	0.3	0.1
Total System Demand (MGD)	0.379	0.588	0.388
Range of Elevations (ft)	74.1	52.8	168.1

The critical value, $t_{\alpha, df}$, is found after calculating the necessary degree of freedom (df) for each test. The equation used to calculate the degrees of freedom is shown in Equation A-2, and the calculated values are displayed in Table A.5.

$$df = \frac{\left(s_1^2/n_1 + s_2^2/n_2\right)^2}{\left[\left(s_1^2/n_1\right)^2/(n_1-1)\right] + \left[\left(s_2^2/n_2\right)^2/(n_2-1)\right]} \quad \text{(A-2)}$$

Table A.5: Degrees of Freedom for System Parameters.

System Parameter	Loop	Grid	Branch
Number of Tanks	7.964	4.161	4.141
Number of Pumps	7.454	5.772	6.793
Number of Nodes	6.751	4.972	4.392
Total Length of Pipes (miles)	5.700	4.484	4.108
Average Length of Pipes (ft)	6.940	4.370	4.838
Average Pipe Diameter (in)	4.898	5.624	4.193
Average Pipes/Node	4.896	7.884	5.134
Total System Demand (MGD)	6.831	7.995	6.930
Range of Elevations (ft)	7.234	5.497	4.783

The decision for this test differs based on the alternative hypothesis used. If the alternative hypothesis states that $\mu_1 > \mu_2$, the null hypothesis (H_o) should be rejected if $t > t_{\alpha, df}$ and the null hypothesis should not be rejected if $t \leq t_{\alpha, df}$. If the alternative hypothesis states that $\mu_1 < \mu_2$, the null hypothesis (H_o) should be rejected if $t < -t_{\alpha, df}$ and the null hypothesis should not be rejected if $t \geq -t_{\alpha, df}$. This information is also displayed in Table 2.6. Table A.6 shows both the calculated t value and critical t values for each t-test performed in this study. Table A.7 shows the decision for each t-test performed.

Table A.6: Values used in t-testing.

System Parameter	Loop & Grid		Loop & Branch		Grid & Branch	
	t	t α, df	t	t α, df	t	t α, df
Number of Tanks	0.134	1.861	-3.263	2.113	-3.293	2.116
Number of Pumps	-0.516	1.880	-4.972	1.959	-4.308	1.905
Number of Nodes	0.594	1.907	-1.345	2.018	-1.632	2.086
Total Length of Pipes (miles)	0.438	1.965	-3.059	2.075	-3.248	2.119
Average Length of Pipes (ft)	-0.584	1.898	-2.970	2.089	-2.672	2.034
Average Pipe Diameter (in)	-1.113	2.000	2.000	1.970	1.895	2.101
Average Pipes/Node	-0.707	2.027	-0.064	1.864	0.667	2.005
Total System Demand (MGD)	0.383	1.903	0.832	1.86	0.260	1.898
Range of Elevations (ft)	-0.779	1.887	-3.075	1.98	-2.804	2.04

Table A.7: Decision for t-tests.

System Parameter	Loop & Grid	Loop & Branch	Grid & Branch
Number of Tanks	Do not reject Ho	Reject Ho	Reject Ho
Number of Pumps	Do not reject Ho	Reject Ho	Reject Ho
Number of Nodes	Do not reject Ho	Do not reject Ho	Do not reject Ho
Total Length of Pipes (miles)	Do not reject Ho	Reject Ho	Reject Ho
Average Length of Pipes (ft)	Do not reject Ho	Reject Ho	Reject Ho
Average Pipe Diameter (in)	Do not reject Ho	Reject Ho	Do not reject Ho
Average Pipes/Node	Do not reject Ho	Do not reject Ho	Do not reject Ho
Total System Demand (MGD)	Do not reject Ho	Do not reject Ho	Do not reject Ho
Range of Elevations (ft)	Do not reject Ho	Reject Ho	Reject Ho

The interpretation of the results of the hypothesis tests are shown in Table A.8 (also shown in Table 2.7). An "L" represents loop systems, "G" is for grid systems, and "B" represents branch networks. If the letters are equal, the null hypothesis was not rejected and there is not enough evidence to prove a difference in the system parameters. If an inequality sign is present, the null hypothesis was rejected, meaning and there was enough evidence to conclude that one configuration had a higher value for the system parameter at the 5% significance level. Analysis and discussion of these results is included in Chapter 2.

Table A.8: Interpretation of Statistical Testing.

System Parameter	Loop & Grid	Loop & Branch	Grid & Branch
Number of Tanks	L=G	L<B	G<B
Number of Pumps	L=G	L<B	G<B
Number of Nodes	L=G	L=B	G=B
Total Length of Pipes (miles)	L=G	L<B	G<B
Average Length of Pipes (ft)	L=G	L<B	G<B
Average Pipe Diameter (in)	L=G	L>B	G=B
Average Pipes/Node	L=G	L=B	G=B
Total System Demand (MGD)	L=G	L=B	G=B
Range of Elevations (ft)	L=G	L<B	G<B

As discussed in Chapter 2, this study also investigated if system parameters, such as number of pumps or total length of water lines, had any correlation with topography of the area (hilly vs. flat regions). A two-sided t-test at the alpha=0.05 significance level was performed to compare each system parameter with the range in elevation for the system to conclude if there was a linear relationship between elevation range and any system parameters. The calculated t values along with the t critical values are shown in Table A.9.

Table A.9: Values used in t-testing (System Parameters vs. Elevation Range)

System Parameter	Loop & Grid		Loop & Branch		Grid & Branch		All Systems	
	t	$t_{\alpha/2, df}$	t	$t_{\alpha/2, df}$	t	$t_{\alpha/2, df}$	t	$t_{\alpha/2, df}$
Number of Tanks	2.570	3.182	-1.070	3.182	0.640	3.182	3.64	1.771
Number of Pumps	1.360	3.182	-0.480	3.182	0.250	3.182	3.85	1.771
Number of Nodes	0.820	3.182	-0.740	3.182	-1.070	3.182	0.56	1.771
Total Length of Pipes (miles)	0.630	3.182	-0.860	3.182	-0.760	3.182	2.34	1.771
Average Length of Pipes (ft)	-0.110	3.182	0.600	3.182	0.840	3.182	4.34	1.771
Average Pipe Diameter (in)	0.190	3.182	-1.430	3.182	0.900	3.182	-2.36	1.771
Average Pipes/Node	-6.730	3.182	-1.510	3.182	-0.860	3.182	-3.51	1.771

The R squared values for these relationships under investigation are also provided in Table A.10.

Table A.10: R^2 Values (System Parameters vs. Elevation Range)

System Parameter	Loop	Grid	Branch	All systems
Number of Tanks	0.6882	0.2768	0.1193	0.5053
Number of Pumps	0.3816	0.0709	0.02	0.5326
Number of Nodes	0.1823	0.1552	0.2747	0.0232
Total Length of Pipes (mi)	0.1178	0.1972	0.1628	0.2956
Average Length of Pipes (ft)	0.0037	0.1058	0.189	0.5912
Weighted Pipe Diameter (in)	0.0123	0.406	0.212	0.2992
Average Pipes/Node	0.9379	0.4309	0.198	0.4866

The decision for the statistical testing to determine if there is a relationship between the system parameters and the elevation range in the system is shown in Table A.11. The null hypothesis states that there is no linear relationship (H_o: $\mu_1 = \mu_2$), and the alternative hypothesis states that there is a linear relationship between the system parameter and range in elevation (H_a: $\mu_1 \neq \mu_2$). The null hypothesis is rejected if $|t| > t_{\alpha/2,df}$ and the null hypothesis is not rejected if $|t| \leq t_{\alpha/2,df}$. The discussion of these results is included in Chapter 2.

Table A.11: Decision for t-tests (System Parameters vs. Elevation Range)

System Parameter	Loop	Grid	Branch	All systems
Number of Tanks	Do not Reject H_o	Do not Reject H_o	Do not Reject H_o	Reject H_o
Number of Pumps	Do not Reject H_o	Do not Reject H_o	Do not Reject H_o	Reject H_o
Number of Nodes	Do not Reject H_o	Do not Reject H_o	Do not Reject H_o	Do not Reject H_o
Total Length of Pipes (mi)	Do not Reject H_o	Do not Reject H_o	Do not Reject H_o	Reject H_o
Average Length of Pipes (ft)	Do not Reject H_o	Do not Reject H_o	Do not Reject H_o	Reject H_o
Weighted Pipe Diameter (in)	Do not Reject H_o	Do not Reject H_o	Do not Reject H_o	Reject H_o
Average Pipes/Node	Reject	Do not Reject H_o	Do not Reject H_o	Reject H_o

Appendix B

Sensor Placement Guidance Procedure

This appendix outlines the developed sensor placement guidance procedure for the placement of one sensor (after the correct system configuration is identified). Both the graphical and full, simplified procedures are included, along with the procedures displayed in flowcharts and examples showing execution of the procedure for a network in each system configuration.

Once the correct system configuration is determined, a procedure is executed in order to find the recommended sensor placement. The procedure for each system configuration follows the same general steps, but certain details and equations vary among the configurations. The general procedure first selects an "ideal" tank. This selects the tank in the network where the best sensor locations are theoretically near. The next major step in the procedure draws a circle around the ideal tank and all nodes located within the circle are considered possible sensor locations. Drawing the circle around one tank in the system drastically reduces the number of possible sensor locations, centering the continued process on a small group of nodes to make the next step manageable and eliminate many options that are likely not effective sensor locations.

The remaining steps are consistent for all three system configurations. Easily measurable parameters are collected for every node within the radius, 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. This procedure for each system configuration is outlined in the following sections.

The outlined sensor placement guidance includes an alternative procedure for those wishing to spend minimal time and resources on the sensor placement process. This procedure will not be as reliable as the full five step process, and it will also not provide a list of ranked nodes for potential sensor locations, which would be helpful if the ideal node is not suitable for placement of a sensor. This shortened method, referred to as the "graphical procedure", still requires the user to execute the ideal tank selection step. Once the ideal tank is selected, an equation is used to provide the user a recommended distance between the ideal tank and the best location for sensor placement. This recommended distance will follow the water lines from the tank to the ideal placement. Therefore, the user should measure this recommended distance from the ideal tank and place the sensor at the nearest feasible location. This graphical procedure will also be outlined in detail in the following sections as step #1a.

B.1 Sensor Placement Guidance Procedure for Loop Systems

The following steps should be executed to determine the optimal placement of one water quality sensor for loop configured systems.

1. Select the "ideal" tank. All storage tanks in the system should be considered candidates for the ideal tank. Assign one point to each tank that best fits the criteria listed below. In the case where more than one tank best fits the criteria, a point should be awarded for both tanks. For example, 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 for criteria #5.

1) Furthest downstream from the source/Water Treatment Plant without being located on the exterior of the system. Figure B.1 shows examples of tanks in loop systems that are located in the exterior of the system (exterior tanks highlighted in red), while Figure B.2 illustrates tanks that are considered interior (interior tanks highlighted in red). If it is difficult to distinguish which tank is furthest downstream of the source/WTP by visual inspection, points can be awarded to multiple tanks. Flow hydraulics does not need to be considered; visual inspection of distance from the source/WTP is adequate.

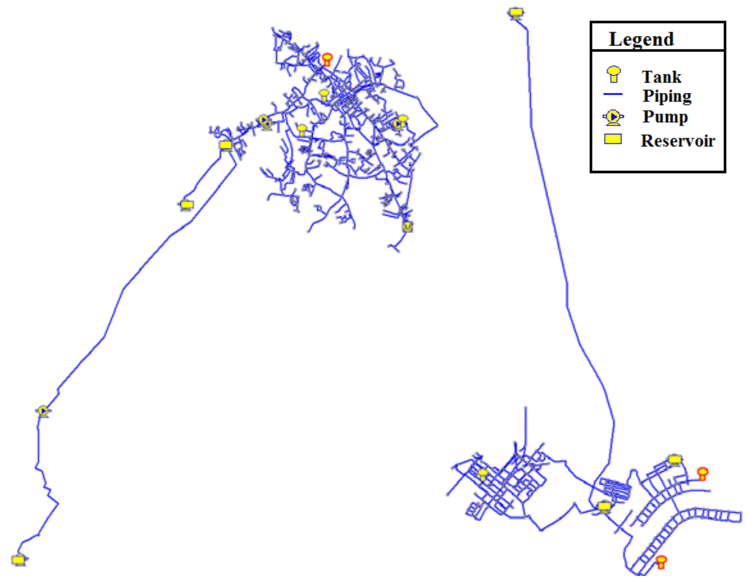


Figure B.1: Examples of Exterior Tanks (Loop Systems).

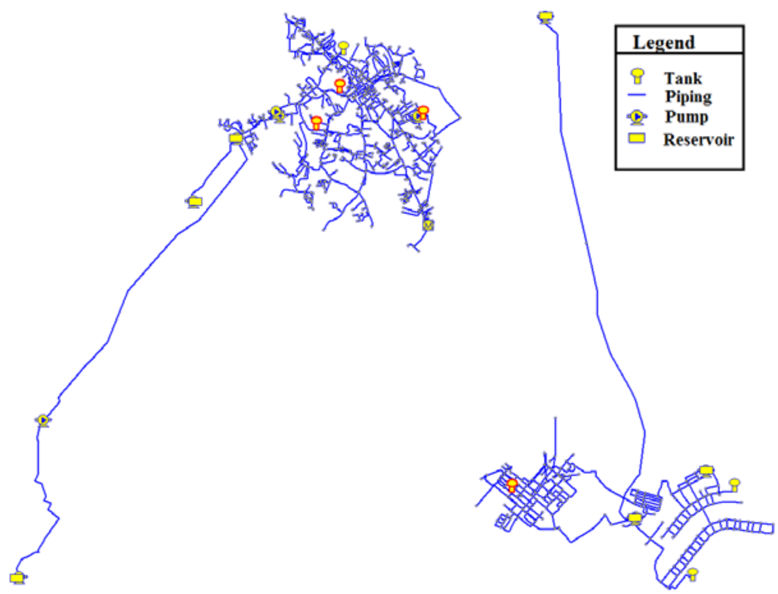


Figure B.2: Examples of Interior Tanks (Loop Systems).

2) Lowest Hydraulic Grade Line (looking at minimum water level in tanks).

3) Lowest Hydraulic Grade Line (looking at maximum water level in tanks).

4) Lowest ground elevation.

5) Smallest (by volume).

Compile the amount of points awarded to each tank in the system. If one tank has a higher number of points than all other tanks in the system, this tank is selected as the ideal tank. If there is a tie for the highest number of points, visual inspection should be made to select the tank that is furthest downstream of the source/WTP without being located on the exterior of the system (criteria #1).

At this point in the procedure the user should decide if they would like to use the graphical procedure for sensor placement or the full procedure. The graphical method will not be as reliable and not provide a list of nodes ranked in terms of their effectiveness as a sensor location, which would be helpful if the ideal node is not suitable for placement of a sensor. The full method will be slightly more time consuming, but it is the most reliable in selecting the ideal node for sensor placement. Users wishing to use the graphical method should follow step 1a, and those wanting to use the extended method should continue to step 2.

1a. Graphical Procedure. To find the optimal distance away from the ideal tank (identified in step 1) to place a sensor, the total length of water lines in the system (in feet) along with the number of tanks in the system is needed. Calculate the loop parameter, L, shown in Equation B-1. In this equation, α = 0.001.

$$L = \alpha \times \left(\frac{Total\ Length\ of\ Water\ Lines\ in\ System\ (ft)}{Number\ of\ Tanks^{2}} \right) \tag{B-1}$$

Then use the loop parameter, L, in Equation B-2 in order to find the recommended distance from the tank.

$$Distance\,(ft) = 28.765 \times e^{(0.0654 \times L)} \tag{B-2}$$

The resulting distance (in feet) is the recommended distance from the ideal tank that a water quality sensor should be placed, following the water lines. 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. Place the sensor at the closest node to this point that is also feasible for placement of a sensor. Nodes are defined as the intersection of any pipes or a location where the pipe diameter or material changes. It should be noted that the sensor should not be placed at a pump, within 500 feet of a pump, or at a dead-end node.

It is possible that there will be multiple pathways to choose as the optimal distance is measured from the ideal tank. This is a slight limitation of the graphical method. If there is a dead-end located in the near vicinity of the ideal tank, the user should choose the pathway in the opposite direction of the dead-end. If the different pathways contain pipes of varying diameters, the pathway containing the largest pipe should be followed. If neither of these conditions is present, the user should attempt to travel in the direction away from the source/Water Treatment Plant. These regulations should be followed in all situations if it is unclear which pathway following the pipelines should be taken. This includes situations where there is more than one pipe connected directly to the ideal tank or if there is only one pipe directly connected to the tank but this pipe later intersects with other pipes to create multiple pathways before the recommended distance is reached.

Figure B.3 illustrates this concept. Two systems are shown where multiple pathways are possible traveling away from the ideal tank. The ideal tank and the diameters of water lines are labeled; the correct pathway that should be followed is labeled with black arrows and highlighted in red. In the top portion, 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 path marked by the black arrow because this pathway contains the pipe with the largest diameter.

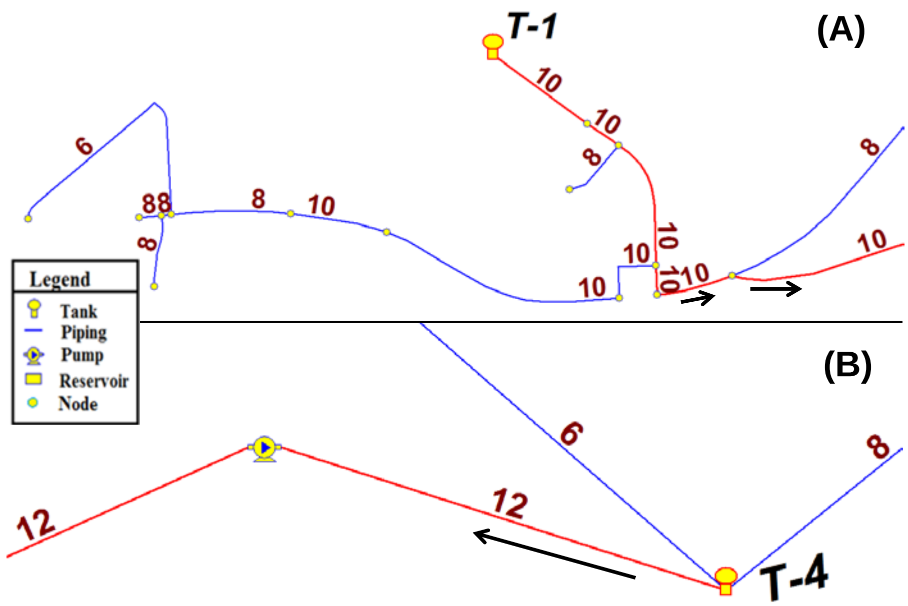


Figure B.3: Correct Pathway Selection in Simple Procedure: (A) KY 7; (B) KY 1.

If the user chose to execute the graphical method, the sensor placement guidance procedure is now complete.

2. Draw circle around ideal tank. An equation is used to determine the necessary radius of the circle around the ideal tank. The total length of water lines in the system (in feet) along with the approximate area the system covers (in square miles) is needed. Use Equation B-3 to calculate the parameter R.

$$R = \frac{Total\ \ Length\ of\ \ Water\ \ Lines\ in\ System\ (\ ft)}{Approximate\ \ Area\ the\ System\ Covers\ (mi^2)} \tag{B-3}$$

Use the calculated parameter, R, to find the required radius based on a set of ranges.

If R ≤ 40000, then Radius = 2500 feet

If 40000 < R ≤ 50000, then Radius = 2000 feet

If 50000 < R ≤ 60000, then Radius = 1500 feet

If R > 60000, then Radius = 1000 feet

Alternatively, an equation can be used to find a more exact value for the radius around the ideal tank. Use the calculated parameter, R, in Equation B-4 to find the required radius.

$$Radius\ (\ ft) = (-0.0494 \times R) + 4149.1 \tag{B-4}$$

If the ideal tank is located on the exterior of the system, the calculated radius should be doubled. It should be noted that criteria #1 of the ideal tank selection step requires the most downstream tank to also be located in the interior of the system. However, the ideal tank can still be located exterior of the system because it is possible one tank fits the majority of the remaining criteria without meeting criteria #1. Draw a circle with the calculated radius around the ideal tank, 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.

3. Define all nodes located within the circle. This list of nodes will act as possible sensor locations. Nodes are defined as the intersection of any pipes or a location where the pipe diameter or material changes. Figure B.4 shows examples of portions of a system where the location of a node is appropriate.

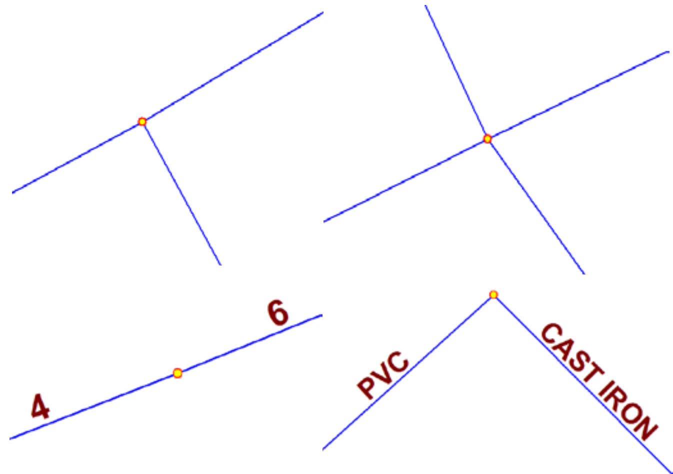


Figure B.4: Examples of Nodes.

Dead-end nodes should not be included in the list of nodes that will be considered possible sensor locations. Pumps should also not be included in this list, as well as nodes within a 500 foot radius of a pump. Figure B.5 shows examples of nodes that should not be included in the list of possible sensor locations.

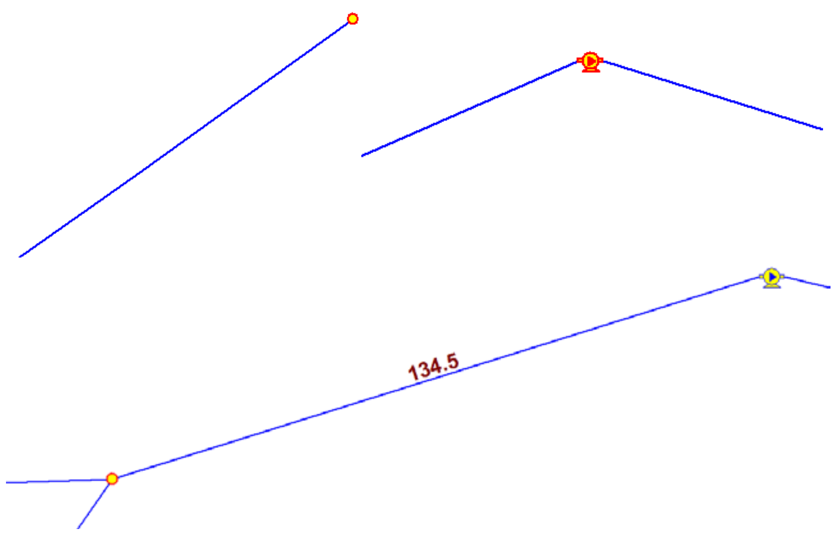


Figure B.5: Examples of Nodes to be Excluded.

All nodes that fit the criteria and are located within the circle drawn around the ideal tank should be included in the list of potential sensor locations. If this list does not contain at least 10 nodes, increase the radius around the tank by 500 foot increments until there are at least 10 nodes for possible sensor locations.

4. Collect data for each node in the circle. Two parameters are needed for each node within the circle that fit the criteria for being a potential sensor location.

1) The shortest distance from the node to the ideal tank, following the water lines. Sum the lengths of each pipeline connecting the node to the tank for a total distance. If multiple pathways are possible from the tank to the node, and it is not obvious which pathway is the shortest, make multiple calculations to select the shortest pathway following the water lines. In most cases, the shortest path will be visually obvious.

2) The number of pipes connected to the node, referred to as the variable N_p. Figure B.6 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.

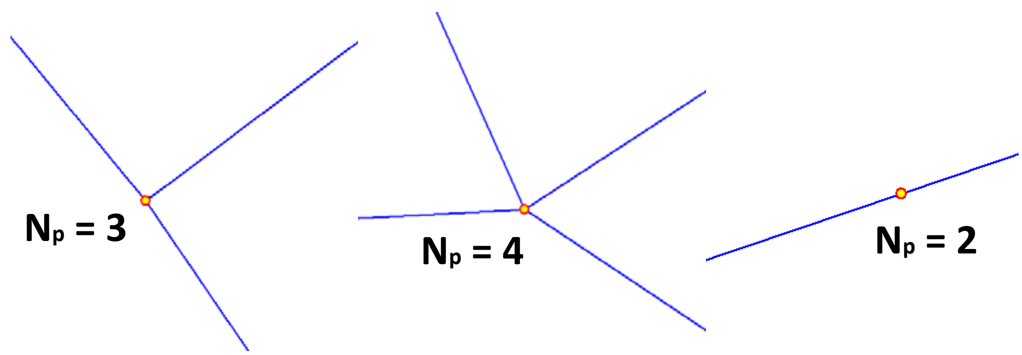


Figure B.6: Examples of the Variable N_p.

For each node, calculate the following parameter shown in Equation B-5.

$$\frac{Distance\ from\ Ideal\ Tank\ to\ Node\ (ft)}{Number\ of\ Pipes\ Connected\ to\ Node} = \frac{Distance}{N_p} \tag{B-5}$$

5. Rank the possible sensor locations. Rank the set of nodes within the circle from the lowest value of Distance/ N_p to the highest value. The node ranked first (lowest value) is considered the optimal sensor location. If sensor placement is not plausible at this location (located at a private home, difficult to access, etc.), use the node that is ranked second. Overall, the node with the lowest value of Distance/ N_p that is accessible and appropriate for placement of a sensor should be considered the optimal sensor location. Excel can be used for this procedure.

B.2 Sensor Placement Guidance Procedure for Grid Systems

The following steps should be executed to determine the optimal placement of one water quality sensor for grid configured systems.

1. Select the "ideal" tank. If the system has five tanks or more, a preliminary step is necessary to selecting the ideal tank. This step is outlined below in part A. If the tank has fewer than five tanks, all tanks should be considered possibilities for the ideal tank, and selection of the ideal tank should be executed by starting at part B.

A. Draw a circle around the entire system. The circle should contain all major system components; however, it is not necessary to include very long distribution mains if the source is significantly far from the remainder of the system. Only areas that contain customer demands should be included. For example, Figure B.7 shows the circle that was drawn for KY 8.

Figure B.7: Circle Drawn Around Grid System (KY 8).

Measure the radius of the circle, and locate the center of the circle. Calculate 40% of the radius (multiply the radius by 0.4). Draw a smaller circle, centered on the center of the large circle, with a radius that is 40% of the larger radius. Eliminate all tanks not contained in the small circle as possibilities for the ideal tank. This process is shown in Figure B.8. The red circle is the large circle, the green dot marks the center of the circle, and the green circle represents the small circle with a radius that is 40% of the large radius. Figure B.8 also shows the location of the five storage tanks in the system. After this process, two of the tanks (located within the green circle) will be considered as possibilities for the ideal tank. The remaining three tanks are no longer options for the ideal tank.

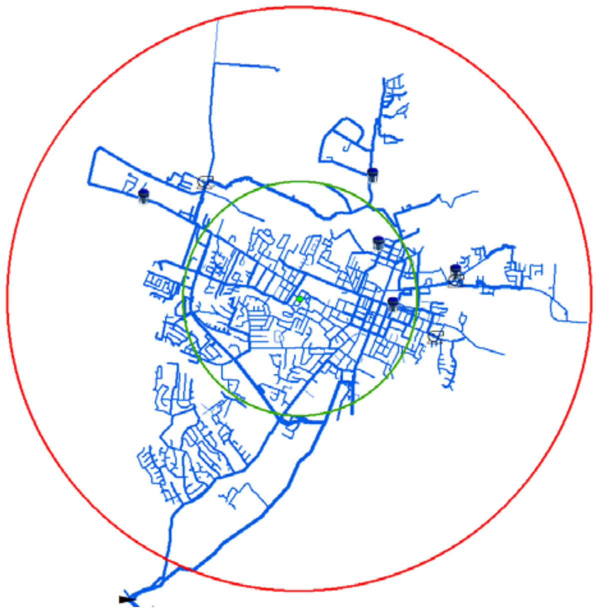


Figure B.8: Preliminary Tank Selection Step (Grid Systems).

After completion of this preliminary step, execute the remainder of the tank selection process by completing step B.

B. Assign one point to each tank that best fits the criteria listed below. In the case where more than one tank best fits the criteria, a point should be awarded for both tanks. For example, 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 for criteria #5.

1) Furthest downstream from the source/Water Treatment Plant. The tank can be located on the interior or exterior of the system. If it is difficult to distinguish which tank is furthest downstream of the source/WTP by visual inspection, points can be

awarded to multiple tanks. Flow hydraulics does not need to be considered; visual inspection of distance from the source/WTP is adequate.

2) Lowest Hydraulic Grade Line (looking at minimum water level in tanks).

3) Lowest Hydraulic Grade Line (looking at maximum water level in tanks).

4) Lowest ground elevation.

5) Smallest (by volume).

6) Smallest pressure head (maximum water level in tank – minimum water level).

Compile the total number of points awarded to each tank in the system. If one tank has a higher number of points than all other tanks in the system, select this tank as the ideal tank. If there is a tie for the highest number of points, use visual inspection to select the tank that is furthest downstream of the source/WTP (criteria #5).

At this point in the procedure the user needs to decide if they would like to use the graphical procedure for sensor placement or the full procedure. The graphical method will be easier to execute but will not be as reliable and not provide a list of nodes ranked in terms of their effectiveness as a sensor location, which would be helpful if the ideal node is not suitable for placement of a sensor. The full method will be slightly more time consuming, but it is the most reliable in selecting the ideal node for sensor placement. Users wishing to use the graphical method should follow step 1a, and those wanting to use the extended method should continue to step 2.

1a. Graphical Procedure. To find the optimal distance away from the ideal tank (identified in step 1) to place a sensor, the total length of water lines in the system (in feet) along with the number of pumps in the system is needed. Calculate the grid parameter, G, shown in Equation B-6. In this equation, α = 0.001.

$$G = \alpha \times \left(\frac{Total\ Length\ of\ Water\ Lines\ in\ System\ (ft)}{Number\ of\ Pumps^2} \right) \tag{B-6}$$

Use the grid parameter, G, in Equation B-7 in order to find the recommended distance from the tank.

$$Distance\,(ft) = 311.14 \times e^{(0.0065 \times G)} \tag{B-7}$$

The resulting distance (in feet) is the recommended distance from the ideal tank that a water quality sensor should be placed, following the water lines. 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. Place the sensor at the closest node to this point that is also feasible for placement of a sensor. Nodes are defined as the intersection of any pipes or a location where the pipe diameter or material changes. It should be noted that the sensor should not be placed at a pump, within 500 feet of a pump, or at a dead-end node.

It is possible that there will be multiple pathways to choose as the optimal distance is measured from the ideal tank. This is another limitation of the graphical method. If there is a dead-end located in the near vicinity of the ideal tank, the user should choose the pathway that moves away from the dead-end. If the different pathways contain pipes of varying diameters, the pathway following the largest pipes should be followed. If neither of these conditions is present, the user should attempt to travel in the direction away from the source/Water Treatment Plant. These regulations should be followed in all situations if it is unclear which pathway following the pipelines should be taken. This includes situations where there is more than one pipe connected directly to the ideal tank or if there is only one pipe directly connected to the tank but this pipe later intersects with other pipes to create multiple pathways before the recommended distance is reached. This concept is illustrated in Figure B.3.

If the user chose to execute the graphical method, the sensor placement guidance procedure is now complete.

2. Draw circle around ideal tank. An equation is used to determine the necessary radius of the circle. The total length of water lines in the system (in feet) along with the approximate area the system covers (in square miles) is needed. First use Equation B-8 to calculate the parameter R.

$$R = \frac{Total\ \ Length\ of\ \ Water\ \ Lines\ in\ System\ (ft)}{Approximate\ \ Area\ the\ System\ Covers\ (mi^2)} \tag{B-8}$$

Use the calculated parameter, R, to find the required radius based on a set of ranges.

If R ≤ 40000, then Radius = 2500 feet

If 40000 < R ≤ 50000, then Radius = 2000 feet

If 50000 < R ≤ 60000, then Radius = 1500 feet

If R > 60000, then Radius = 1000 feet

Alternatively, an equation can be used to find a more exact value for the radius around the ideal tank. Use the calculated parameter, R, in Equation B-9 to find the required radius.

$$Radius\ (ft) = (-0.0494 \times R) + 4149.1 \quad \text{(B-9)}$$

If the ideal tank is located on the exterior of the system, the calculated radius needs to be doubled. Figure B.9 shows examples of grid systems with tanks considered interior highlighted in red, and Figure B.10 shows the same systems with exterior tanks highlighted in red.

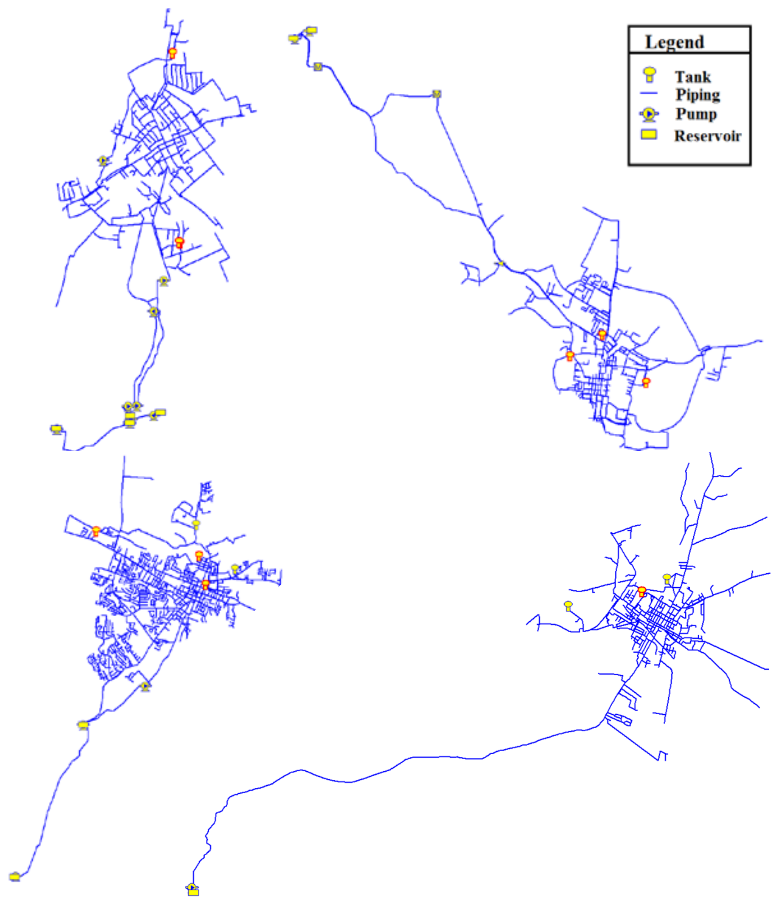


Figure B.9: Example of Interior Tanks (Grid Systems).

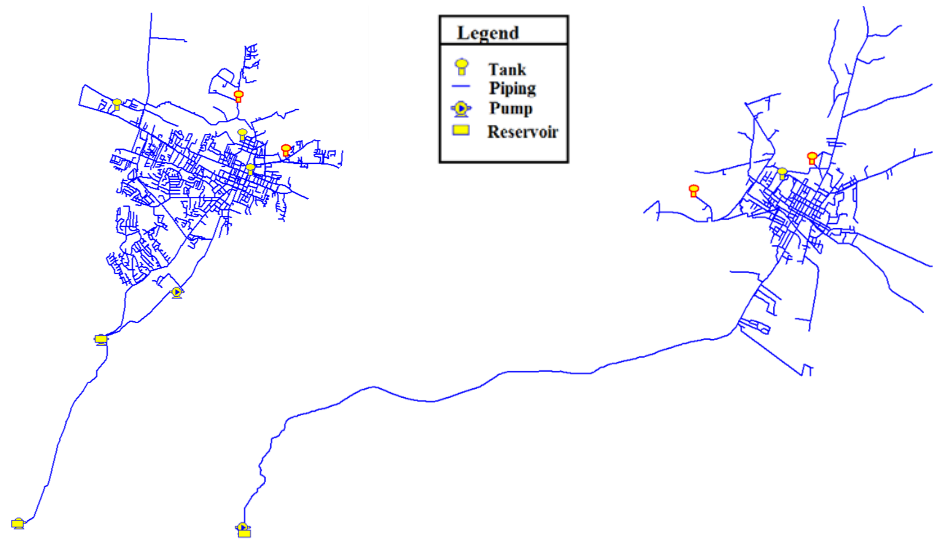


Figure B.10: Example of Exterior Tanks (Grid Systems).

Draw a circle with the calculated radius around the ideal tank, 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.

3. Define all nodes located within the circle. This list of nodes will act as possible sensor locations. Nodes are defined as the intersection of any pipes or a location where the pipe diameter or material changes. Figure B.4 shows examples of portions of a system where the location of a node is appropriate. Dead-end nodes should not be included in the list of nodes that will be considered possible sensor locations. Pumps should also not be included in this list, as well as nodes within a 500 foot radius of a pump. Figure B.5 shows examples of nodes that should not be included in the list of possible sensor locations.

All nodes that fit the criteria and are located within the circle drawn around the ideal tank should be included in the list of potential sensor locations. If this list does not contain at least 10 nodes, increase the radius around the tank by 500 foot increments until there are at least 10 nodes for possible sensor locations.

4. Collect data for each node in the circle. Two parameters are needed for each node within the circle that fit the criteria for being a potential sensor location.

1) The shortest distance from the node to the ideal tank, following the water lines. Sum the length of each pipeline connecting the node to the tank for a total distance. If multiple pathways are possible from the tank to the node, and it is not obvious which pathway is the shortest, make multiple calculations to select the shortest pathway following the water lines. In most cases, the shortest path will be visually obvious.

2) The number of pipes connected to the node, referred to as the variable N_p. Figure B.6 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.

For possible sensor location, calculated the following parameter in Equation B-10.

$$\frac{Distance\ from\ Ideal\ Tank\ to\ Node\ (ft)}{Number\ of\ Pipes\ Connected\ to\ Node} = \frac{Distance}{N_p} \tag{B-10}$$

5. Rank the possible sensor locations. Rank the set of nodes within the circle from the lowest value of Distance/ N_p to the highest value. The node ranked first (lowest value) is considered the optimal sensor location. If sensor placement is not plausible at this location (located at a private home, difficult to access, etc.), the node that is ranked second should be used. Overall, the node with the lowest value of Distance/ N_p that is accessible and appropriate for placement of a sensor should be considered the optimal sensor location. Excel can be used for this procedure.

B.3 Sensor Placement Guidance Procedure for Branch Systems

The following steps should be executed to determine the optimal placement of one water quality sensor for branch configured systems. If the system has 20 tanks or more, sensor placement cannot be recommended using this method. It is recommended to build a model of the network and use the sensor placement tool in KYPIPE or utilize the TEVA-SPOT software. If a network has less than 20 storage tanks, the procedure outlined below can be used.

1. Select the "ideal" tank. This process for ideal tank selection in branch systems is slightly more complex than for loop and grid systems. Selection of the ideal tank requires several steps that are outlined below.

A. Draw a circle around the entire system, ensuring it is the smallest possible circle while still including all components. Examples of this circle for branch systems are displayed in Figure B.11.

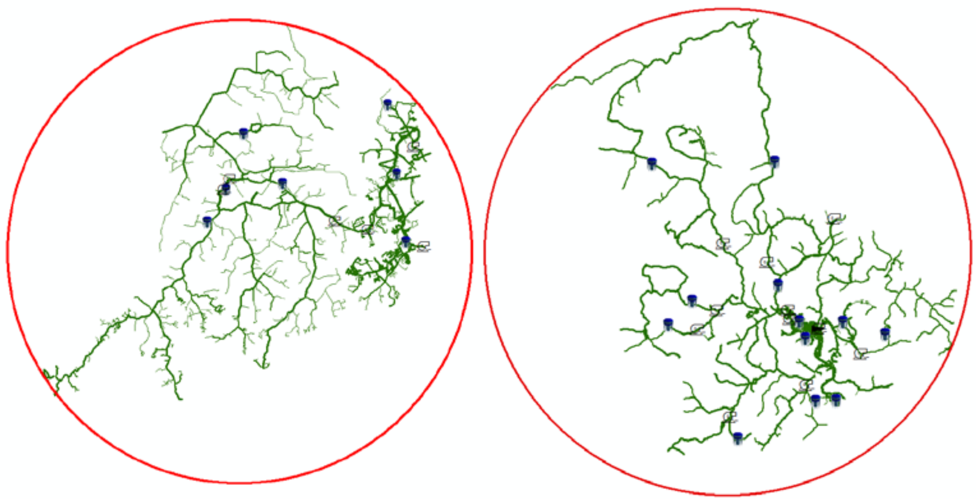


Figure B.11: Example of Circle to Encompass System (Branch Systems).

Locate and mark the center of the circle, and also measure the radius of the circle. Next, draw a smaller circle centered at the center of the large circle. To calculate the required radius for the smaller circle, the total length of pipelines in the system along with the radius of the large circle is needed. Use this information to calculate the parameter, P, shown in Equation B-11.

$$P = \frac{\textit{Total Length of Water Lines in System (ft)}}{\textit{Radius of Large Circle to Cover Entire System (ft)}} \qquad \text{(B-11)}$$

Use the calculated parameter, P, to find the percentage of the large radius that is needed to find the value of the smaller radius (Equation B-12). Once the percentage is found, multiply the value by the large radius to find the smaller radius (Equation B-13). Note that the value found for percentage is in decimal form, so it is not necessary to divide the value by 100 before it is multiplied by the large radius.

$$Percentage = (-0.0086 \times P) + 0.715 \qquad \text{(B-12)}$$

$$Small\ Radius\ (ft) = Percentage \times Large\ Radius\ (ft) \qquad \text{(B-13)}$$

Draw a smaller circle, centered on the center of the large circle, with the calculated radius. Eliminate all tanks that are not located within the small circle as possibilities for the ideal tank. This process is shown in Figure B.12. The red circle is the large circle, the red dot marks the center of the circle, and the blue circle represents the small circle. Figure B.12 also shows the location of the storage tanks in the system. After this process, only seven of the tanks (located within the blue circle) will be considered as possibilities for the ideal tank.

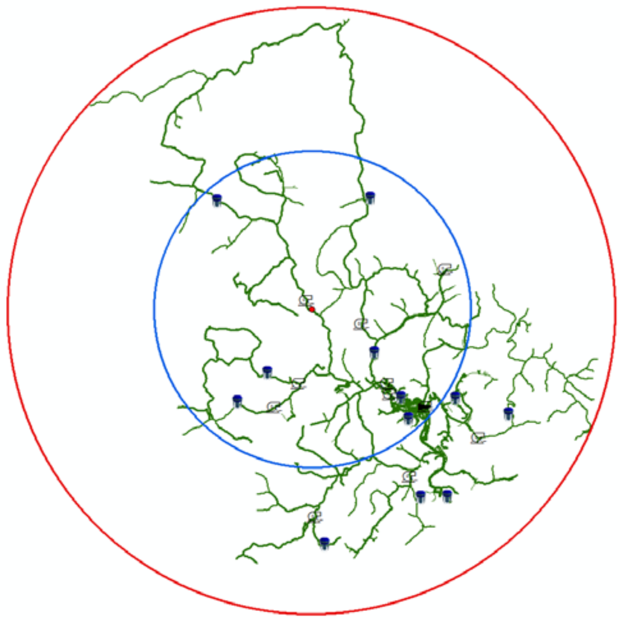


Figure B.12: Preliminary Tank Selection Step (Branch Systems).

After completion of step A, carry out the remainder of the tank selection process by proceeding to step B.

B. Assign one point to each tank that best fits the criteria listed below. In the case where more than one tank best fits the criteria, a point should be awarded for both tanks.

1) Lowest ground elevation.

2) Lowest Hydraulic Grade Line (looking at minimum water level in tanks).

3) Lowest Hydraulic Grade Line (looking at maximum water level in tanks).

4) Located within 2000 feet of a pump (straight distance, does not need to follow water lines).

5) Located in a downtown area. This is only applicable if the system has an easily distinguishable downtown area that is significantly denser than the rest of the system.

This area will also typically have a grid-like pattern. An example of this concept is illustrated in Figure B.13.

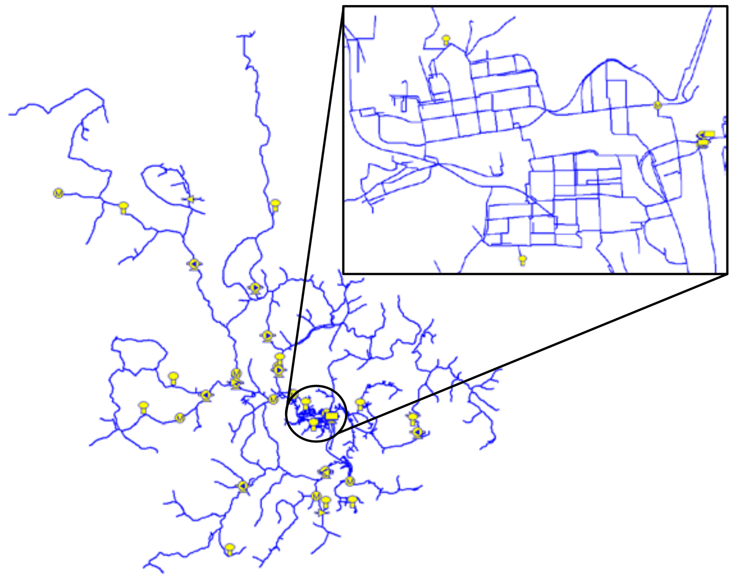


Figure B.13: Example of Downtown Area (Branch Systems).

Compile the amount of points awarded to each tank in the system. If one tank has a higher number of points than all other tanks in the system, select this tank as the ideal tank. If there is a tie for the highest number of points, the tank with the lowest hydraulic grade line looking at minimum water level in the tank should be selected (criteria #2).

At this point in the procedure, the user needs to decide if they would like to use the graphical procedure for sensor placement or the full procedure. The graphical method will not be as reliable and not provide a list of nodes ranked in terms of their effectiveness as a sensor location, which would be helpful if the ideal node is not suitable for placement of a sensor. The full method will be slightly more time consuming, but it is the most reliable in selecting the ideal node for sensor placement. Users wishing to use the graphical method should follow step 1a, and those wanting to use the extended method should continue to step 2.

1a. Graphical Procedure. To find the optimal distance away from the ideal tank (identified in step 1) to place a sensor, the user needs specific information about the network. First, the average length of water lines in the system (in feet) is needed, found by dividing the total length of all pipelines in the system by the total number of pipes present. The user also needs the area of the circle needed to encompass the entire system (drawn in step 1 during the ideal tank selection process). Because only the radius of the large circle was measured in step 1, first use Equation B-14 to calculate the area of the circle.

$$A\,(mile^2) = \pi \times R^2 \qquad \text{(B-14)}$$

where A represents the area of the circle to encompass the entire system (mi^2) and R is the radius of this circle (mi). Next, calculate the branch parameter, B, shown in Equation B-15.

$$B = \frac{Area\ of\ Circle\ to\ Cover\ Entire\ System\ (mi^2)}{Average\ Pipe\ Length\ (mi)} \qquad \text{(B-15)}$$

Use the branch parameter, B, in Equation B-16 in order to find the recommended distance from the tank.

$$Distance\,(ft) = 40.705 \times e^{(0.0015 \times B)} \qquad \text{(B-16)}$$

The resulting distance (in feet) is the recommended distance from the ideal tank that a water quality sensor should be placed, following the water lines. Start 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. Place a sensor at the closest node to this point that is also feasible for placement of a sensor. Nodes are defined as the intersection of any pipes or a location where the pipe diameter or material changes. It should be noted that the sensor should not be placed at a pump or dead-end node.

It is possible that there will be multiple pathways to choose as the optimal distance is measured from the ideal tank. This is a slight limitation of the graphical method. If there is a dead-end located in the near vicinity of the ideal tank, the user should choose the pathway that is furthest away from the dead-end. If the different pathways contain pipes of varying diameters, the pathway following the largest pipes should be followed. If neither of these conditions is present, the user should attempt to travel in the direction away from the source/Water Treatment Plant. These regulations should be followed in all situations if it is unclear which pathway following the pipelines should be taken. This includes situations where there is more than one pipe connected directly to the ideal tank or if there is only one pipe directly connected to the tank but this pipe later intersects with other pipes to create multiple pathways before the recommended distance is reached. This concept is illustrated in Figure B.3. If the user chose to execute the graphical method, the sensor placement guidance procedure is now complete.

2. Draw circle around ideal tank. An equation is used to determine the necessary radius of the circle. The area of the large circle drawn to encompass the entire system (completed in the ideal tank selection process) is needed. Use Equation B-17 to calculate the area of the circle using the radius already measured.

$$A\,(mi^2) = \pi \times R^2 \tag{B-17}$$

where A represents the area of the circle to encompass the entire system (mi^2) and R is the radius of this circle (mi). Next, use the area of the circle in Equation B-18 to calculate the radius of the circle to be drawn around the ideal tank.

$$Radius\ (ft) = (7.9892 \times A) + 755.88 \tag{B-18}$$

Draw a small circle around the ideal tank, with the tank as the center of the circle, using the calculated radius. If the ideal tank is located in a downtown area of the network (described in Figure B.13), the calculated radius should first be divided by five. 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.

3. Define all nodes located within the circle. This list of nodes will act as possible sensor locations. Nodes are defined as the intersection of any pipes or a location where the pipe diameter or material changes. Figure B.4 shows examples of portions of a system where the location of a node is appropriate. Dead-end nodes should not be included in the list of nodes that will be considered possible sensor locations. Pumps should also not be included in this list, as well as nodes within 500 feet of a pump (straight distance from pump to node, does not need to follow water lines). Figure B.5 shows examples of nodes that should not be included in the list of possible sensor locations.

All nodes that fit the criteria and are located within the circle drawn around the ideal tank should be included in the list of potential sensor locations. If this list does not contain at least 10 nodes, increase the radius around the tank by 500 foot increments until there are at least 10 nodes for possible sensor locations.

4. Collect data for each node in the circle. Two parameters are needed for each node within the circle that fits the criteria for being a potential sensor location outlined in the previous step.

1) The shortest distance from the node to the ideal tank, following the water lines. Sum the length of each pipeline connecting the node to the tank for a total distance. If multiple pathways are possible from the tank to the node, and it is not obvious which pathway is the shortest, make multiple calculations to select the shortest pathway following the water lines. In most cases, the shortest path will be visually obvious.

2) The number of pipes connected to the node, referred to as the variable N_p. Figure B.6 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.

For each node, calculate the following parameter in Equation B-19.

$$\frac{Distance\ from\ Ideal\ Tank\ to\ Node\ (ft)}{Number\ of\ Pipes\ Connected\ to\ Node} = \frac{Distance}{N_p} \qquad \text{(B-19)}$$

5. Rank the possible sensor locations. Rank the set of nodes within the circle from the lowest value of Distance/ N_p to the highest value. The node ranked first (lowest value) is considered the optimal sensor location. If sensor placement is not plausible at this location (located at a private home, difficult to access, etc.), the node that is ranked second should be used. Overall, the node with the lowest value of Distance/ N_p that is accessible and appropriate for placement of a sensor should be considered the optimal sensor location. Excel can be used for this procedure.

B.4 Flowcharts for Sensor Placement Guidance Procedure

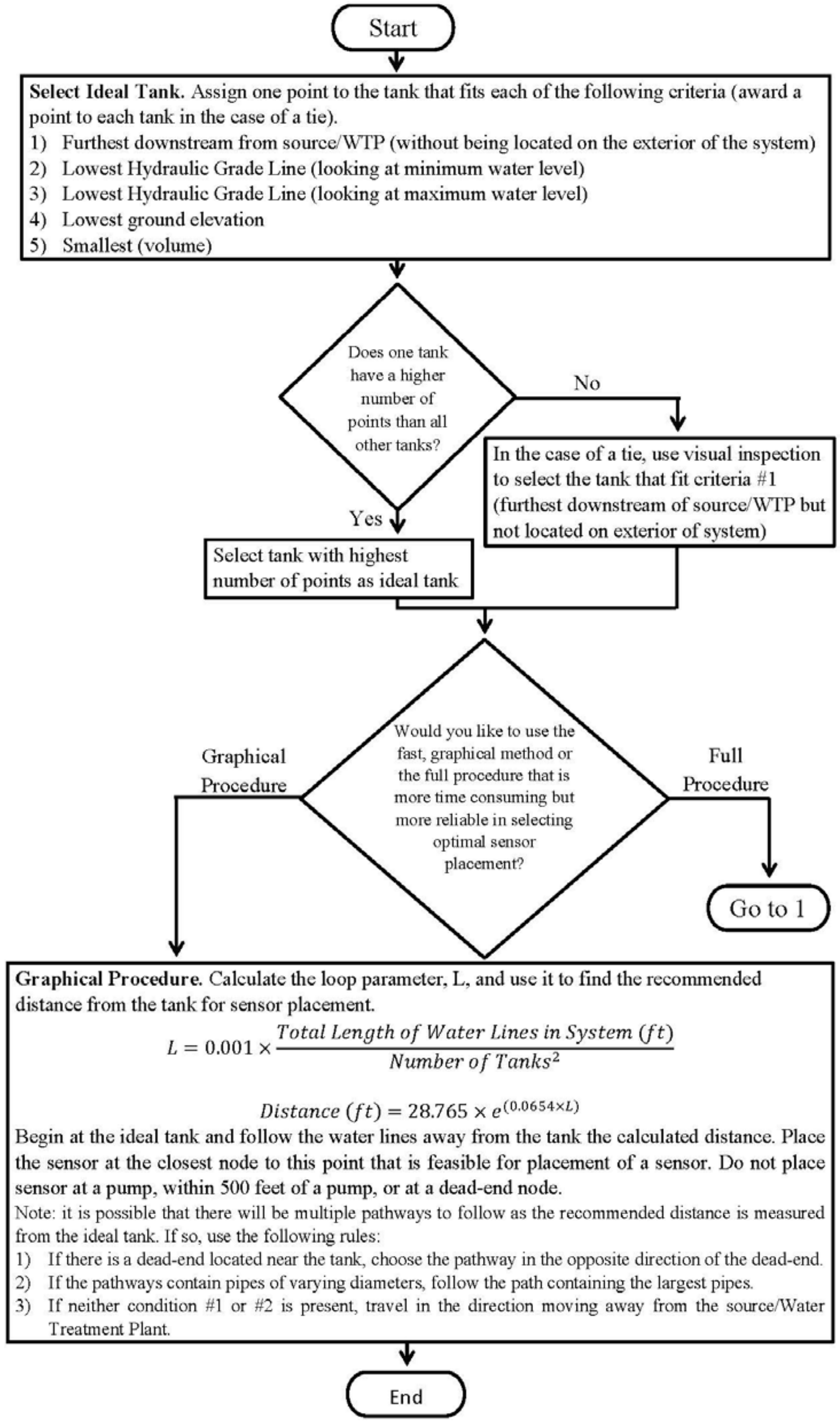


Figure B.14: Sensor Placement Guidance Flowchart for Loop Systems.

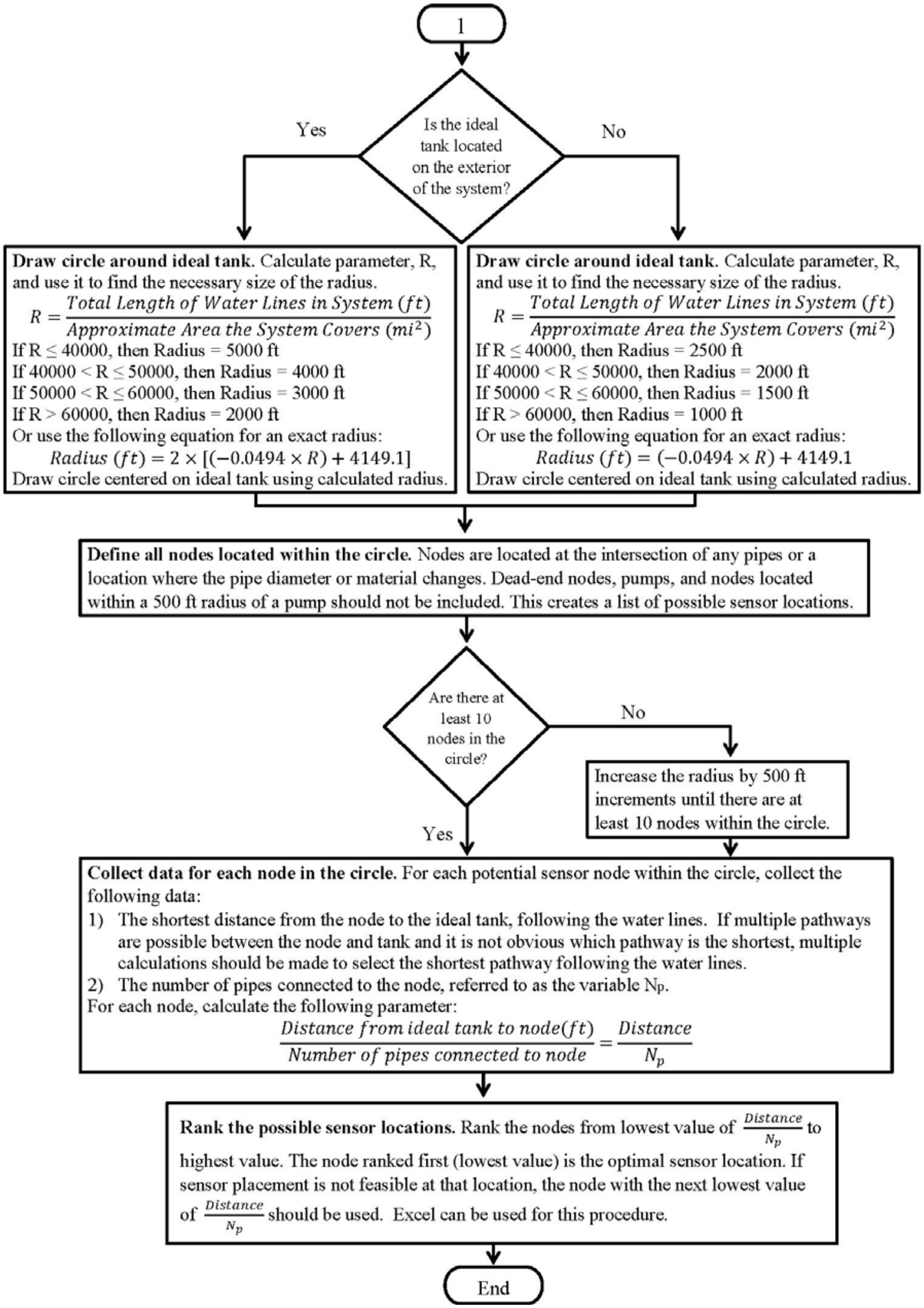


Figure B.15: Sensor Placement Guidance Flowchart for Loop Systems (continued).

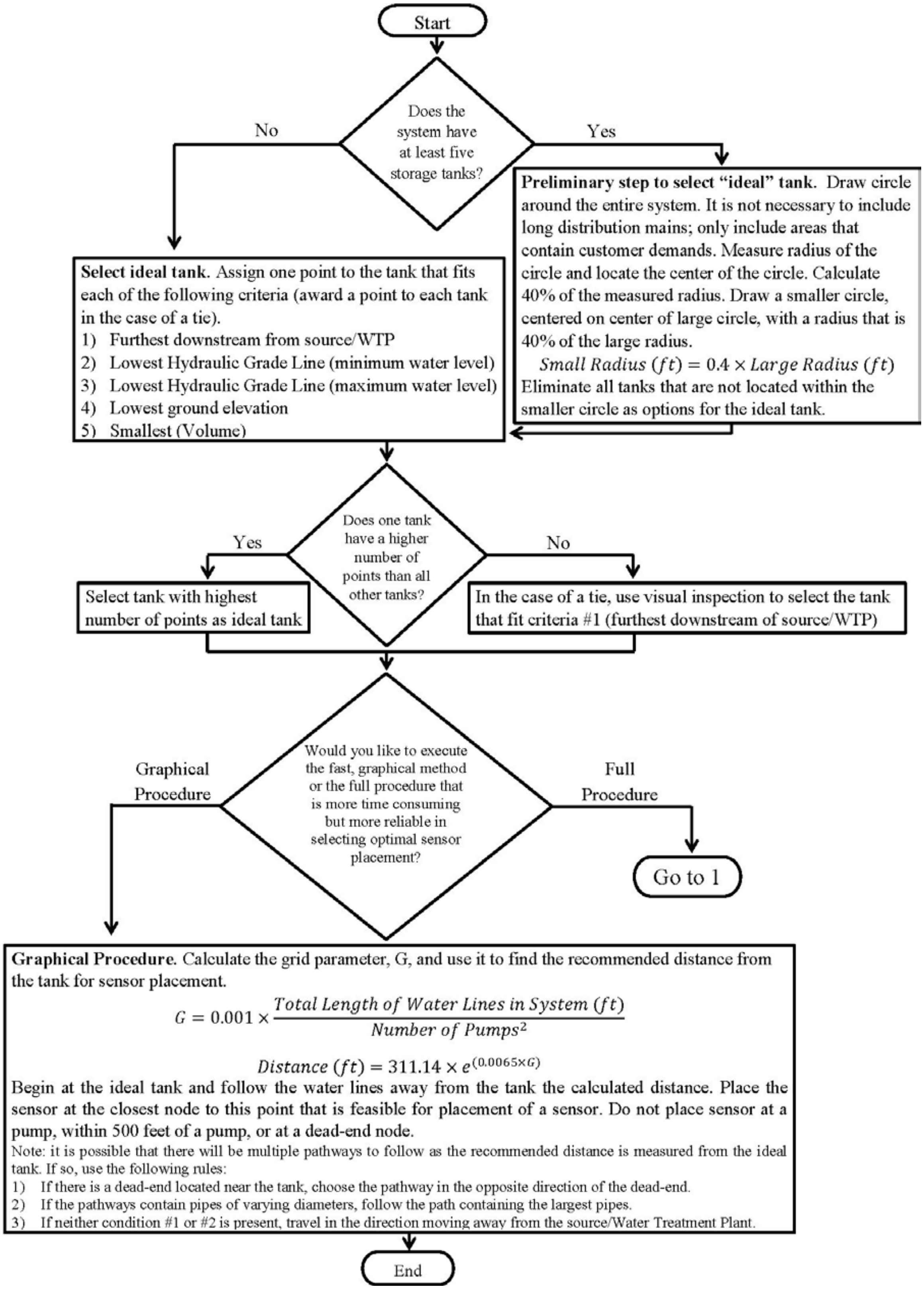


Figure B.16: Sensor Placement Guidance Flowchart for Grid Systems.

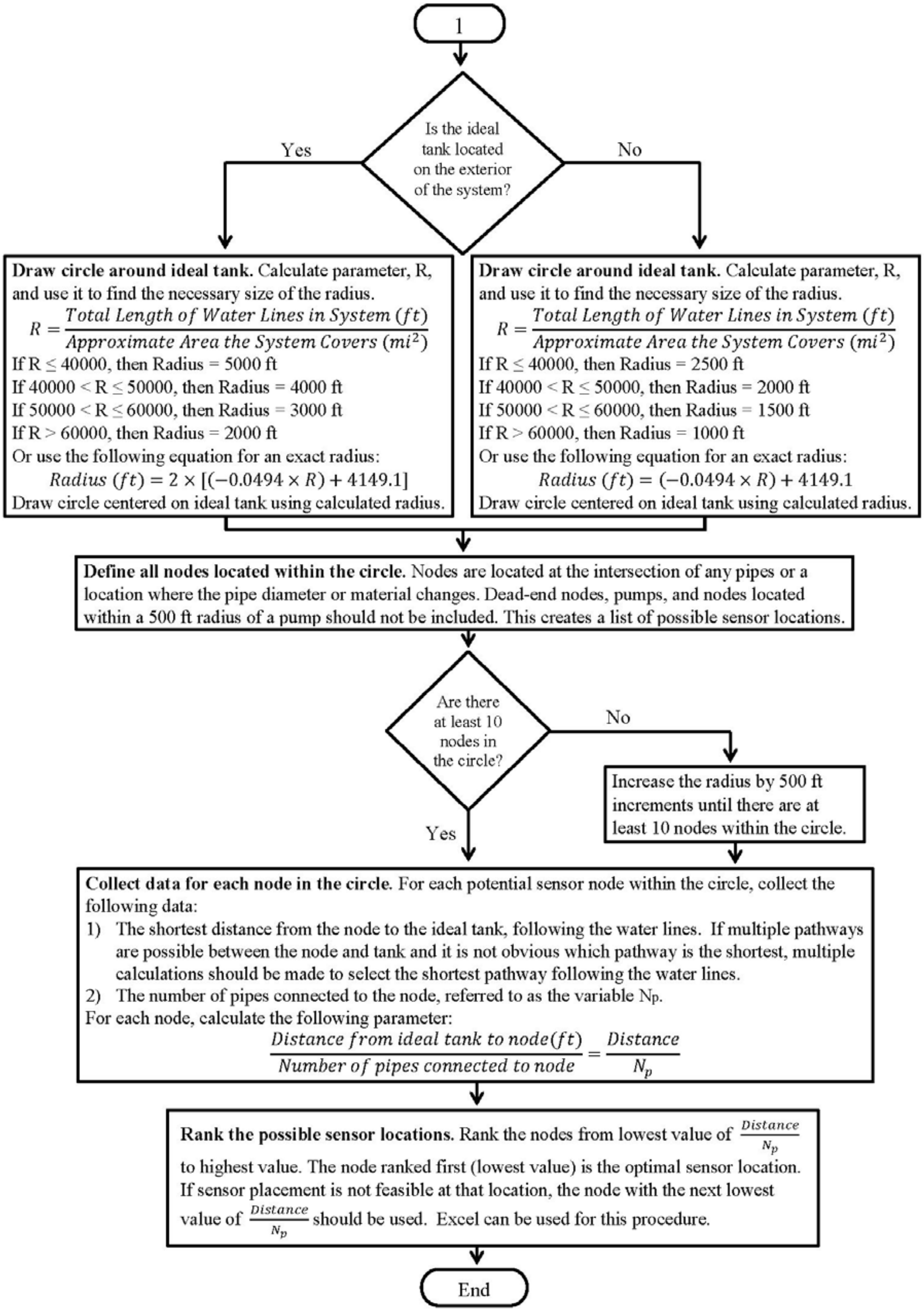


Figure B.17: Sensor Placement Guidance Flowchart for Grid Systems (continued).

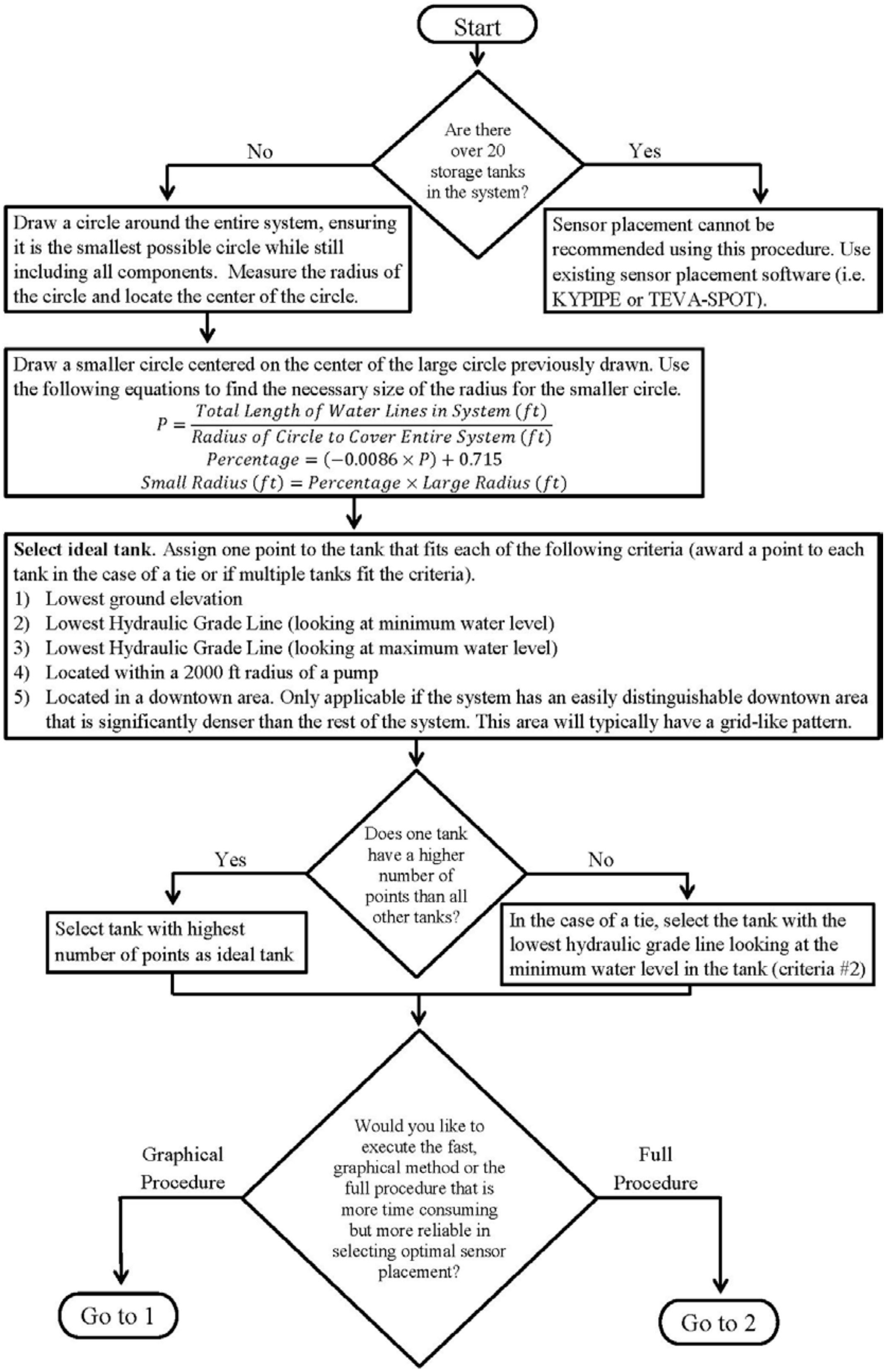


Figure B.18: Sensor Placement Guidance Flowchart for Branch Systems.

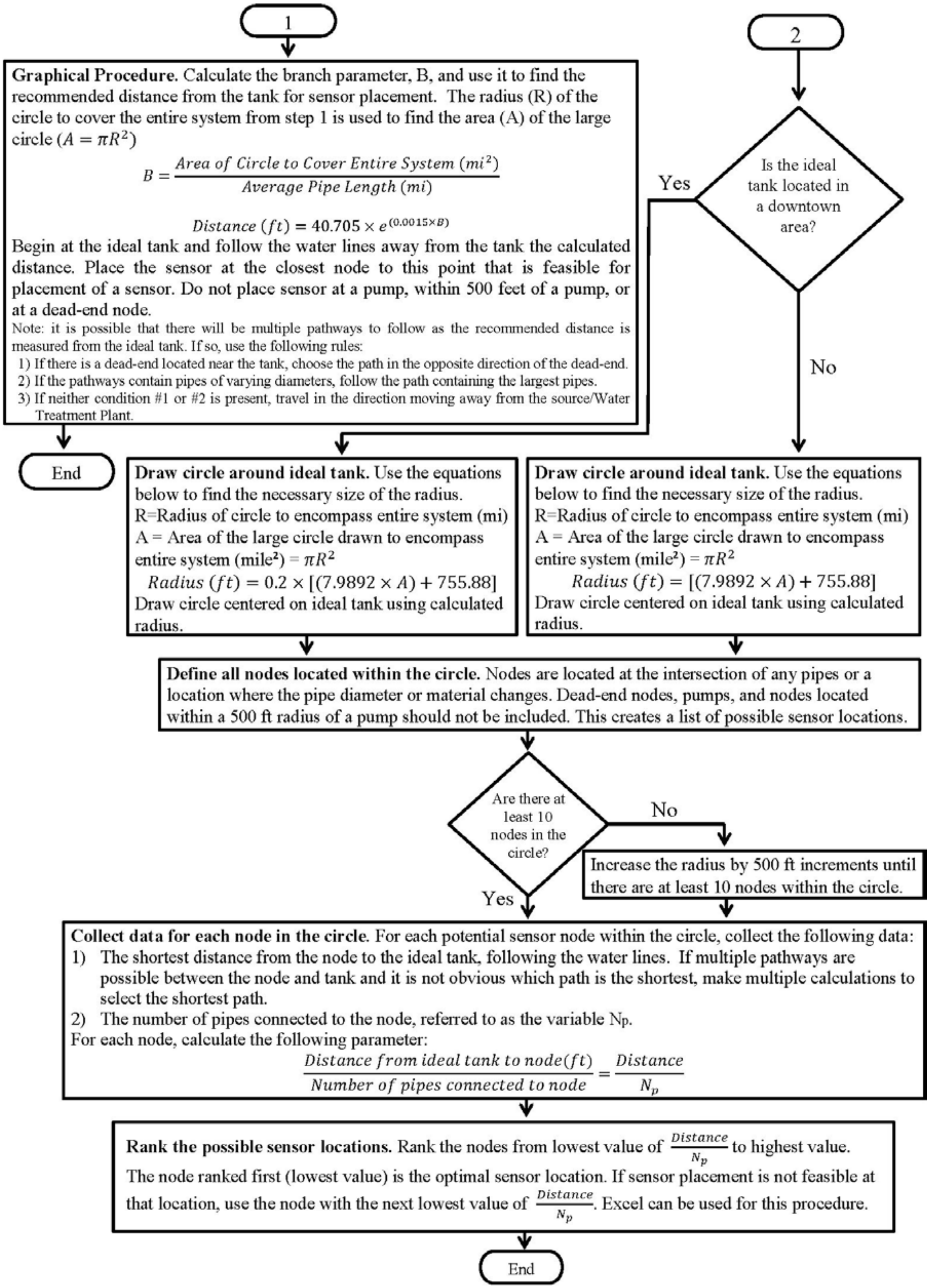


Figure B.19: Sensor Placement Guidance for Branch Systems (continued).

B.5 Example Execution of Procedure on a Loop System

An example of the developed procedure, including both the graphical and full procedure, for loop configured systems using KY 1 is outlined in this section.

1. Select ideal tank. Figure B.20 shows all four tanks that are possibilities for the ideal tank in KY 1. The list of criteria, along with the tank that was awarded a point for each criterion, is outlined below. Table B.1 shows the data for all tanks in the system, including the total number of points each tank was awarded in the tank selection process.

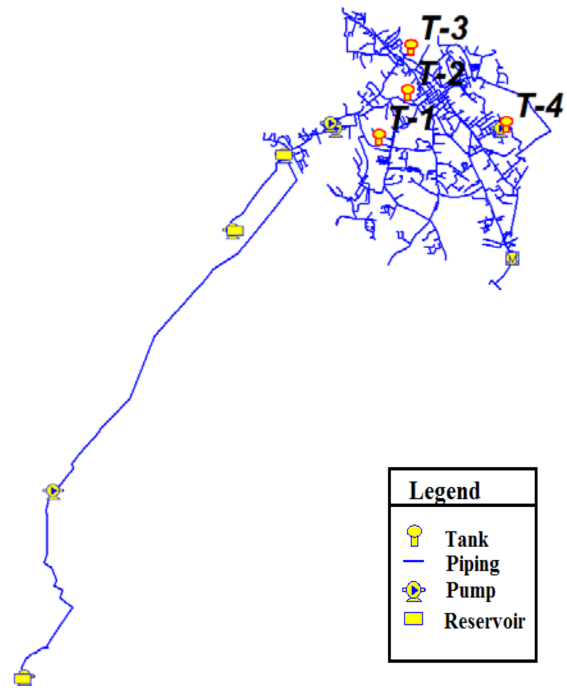


Figure B.20: Possible Ideal Tanks in KY 1.

1) Furthest downstream of source/WTP without being located on exterior of system: T-4. Visual inspection of Figure B.20 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 B.1: Tank Information and Point Total (KY 1).

Tank	Elevation (ft)	HGL (Max level - ft)	HGL (Min level - ft)	Diameter (ft)	Volume (ft^3)	Most Down-stream?	Interior Location?	Point Total
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

It should be noted that the volume of tanks in the KYPIPE models were expressed as a fixed diameter. Therefore, the volume of the tanks was estimated using the equation for volume of a cylinder along with the fixed diameter and pressure head (maximum – minimum water level). If the volume of the tanks (in gallons) is known, these values should be used to determine the smallest tank by volume. T-4 was awarded five points total, which was significantly higher than any other tank. Therefore, T-4 was selected as the ideal tank.

1a. Graphical Procedure. To find the optimal distance away from T-4 (identified in step 1) to place a sensor, the total length of water lines in the system (in feet) along with the number of tanks in the system was needed. The loop parameter, L, was calculated using Equation B-20. In this equation, $\alpha = 0.001$.

$$L = \alpha\left(\frac{Total\ Length\ of\ Water\ Lines\ in\ System\ (ft)}{Number\ of\ Tanks^2}\right) = 0.001\left(\frac{499535\ ft}{3^2}\right) = 55.5 \quad \text{(B-20)}$$

The loop parameter, L, was then used in Equation B-21 in order to find the recommended distance from the tank.

$$Distance\,(ft) = 28.765 \times e^{(0.0654 \times 55.5)} = 1084.48\ ft \quad \text{(B-21)}$$

1084.48 feet is the recommended distance from the ideal tank that a water quality sensor should be placed, following the water lines. When looking at the configuration of KY 1, there are three different pipes connected to T-4. This leaves the user with the challenge of figuring out the best pathway to follow when moving away from T-4. None of the three options led directly to a dead-end, so this condition 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 leading away from the ideal tank. Because one path had a larger pipe than the other pathways, this 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 this node was located 1015.92 feet away from T-4. Therefore, J-235 was selected as the ideal location for a sensor node using the graphical method. The selected node is labeled in Figure B.21, along with the pipe diameters of the water lines connected to T-4.

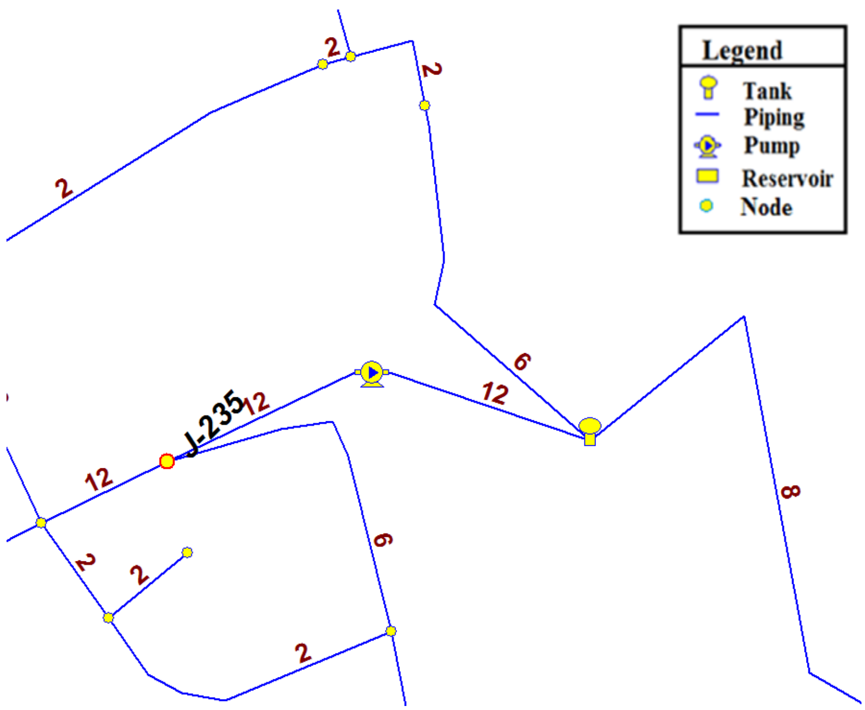


Figure B.21: Sensor Node Selection using the Graphical Procedure (KY 1).

2. Draw circle around ideal tank. The total length of pipes in KY 1 along with the approximate area the system covers was used to calculate the ideal radius. First, the system data was used to calculate the parameter R (Equation B-22).

$$R = \frac{Total\ Length\ of\ \ Pipes\ in\ System\ (ft)}{Approximate\ Area\ the\ System\ Covers\ (mi^2)} = \frac{546969\ ft}{11.8\ mi^2} = 46353.3 \qquad \text{(B-22)}$$

Because this value is between 40,000 and 50,000, an approximation of the ideal radius is 2000 feet (found with the provided ranges). A more exact calculation of the ideal radius was found using the provided equation shown in Equation B-23.

$$Radius = (-0.0494 \times R) + 4149.1 = (-0.0494 \times 46353.3) + 4149.1 = 1859.2 \ ft \qquad \text{(B-23)}$$

Either value for the radius can be used. For this example, the approximation of 2000 feet was used. Because the ideal tank is not an exterior tank, it was not necessary to double the radius. A circle was drawn around the ideal tank using the calculated radius, with the tank located at the center of the circle. This step is shown in Figure B.22. 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.

Figure B.22: Radius around Ideal Tank (KY 1).

3. Define all nodes located within circle. It should be noted that the procedure instructs the user to define nodes at locations where pipes intersect or where the pipe size/material changes. In the KYPIPE models used in this study, nodes are sometimes present at locations that do not fit these criteria. There is typically a demand present, but some nodes present in the KYPIPE models do not have a change of pipe size/material or intersect with other pipes. These nodes will be referred to as “phantom nodes”. They will be included in the study and considered as possible sensor locations, but a typical utility manager carrying out this procedure would not include them in the list of possible sensor locations. In this example illustrating KY 1, there are 23 nodes located within the circle. If the “phantom nodes” are not included, there would only be 20 nodes listed as possible sensor locations. Figure B.23 displays the nodes located in the circle centered on the ideal tank in KY 1.

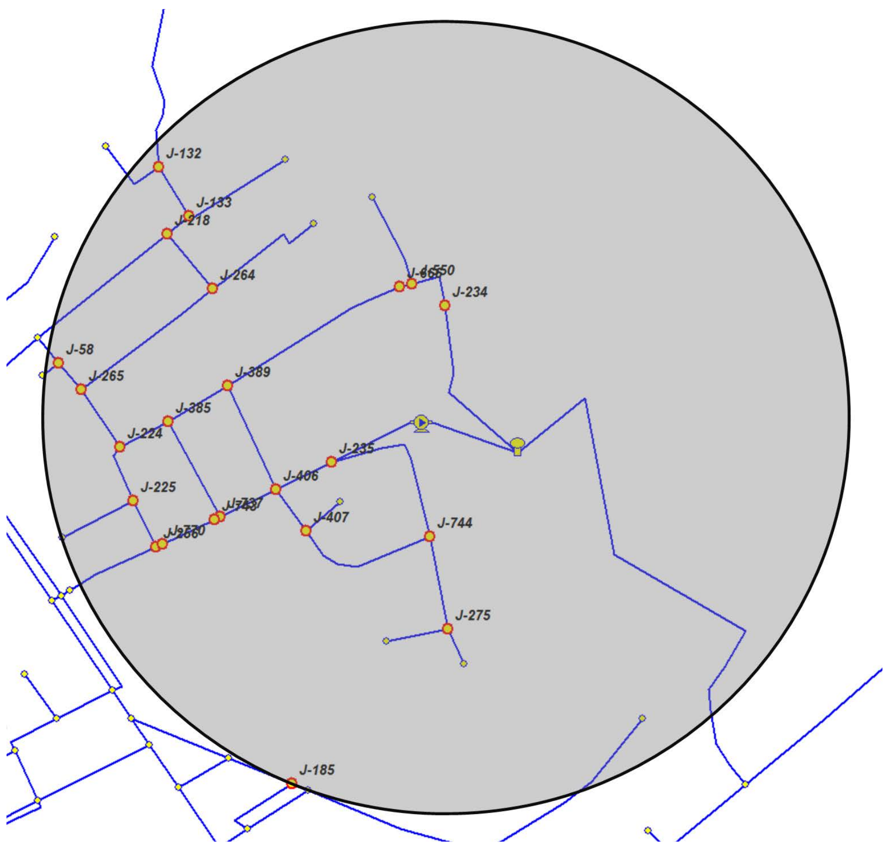


Figure B.23: Nodes Located in Circle (KY 1).

4. Collect data for each node in circle. For each node defined as a potential sensor location, the distance from the ideal tank to the node (following the water lines) was calculated along with the number of pipes connected to the node (N_p). The value of Distance/ N_p was calculated for each node. This data is shown in Table B.2 for the KY 1 system.

Table B.2: Data Collection for Nodes within Circle (KY 1).

Node	N_p	Distance (ft)	Distance / N_p
J-132	3	4499.63	1499.88
J-133	3	4204.55	1401.52
J-185	3	4225.49	1408.50
J-218	3	4060.15	1353.38
J-224	3	2486.38	828.79
J-225	3	2278.42	759.47
J-234	2	917.57	458.79
J-235	3	1015.92	338.64
J-256	3	2013.31	671.10
J-264	3	3694.58	1231.53
J-265	3	2844.3	948.10
J-275	3	2371.33	790.44
J-385	3	2208.93	736.31
J-389	3	1918.27	639.42
J-406	4	1332.35	333.09
J-407	3	1594.84	531.61
J-550	3	1211.12	403.71
J-58	3	3020.59	1006.86
J-666	2	1277.43	638.72
J-737	3	1651.12	550.37
J-743	2	1683.76	841.88
J-744	3	1891.61	630.54
J-770	2	1976.45	988.23

5. Rank the possible sensor locations. The nodes were ranked in terms of increasing values of the Distance/ N_p parameter. The node ranked first, with the lowest value of the parameter, is considered the ideal sensor location. If the ideal node is not suitable for the placement of a sensor, the ranked list can be used to find the next best location. The nodes within the circle ranked in terms of the best sensor locations can be viewed in Table B.3. In the case of KY 1, J-406 was determined to be the ideal node for sensor placement.

Table B.3: Ranked Nodes (KY 1).

Node	N_p	Distance (ft)	Distance / N_p	Ranking
J-406	4	1332.35	333.09	1
J-235	3	1015.92	338.64	2
J-550	3	1211.12	403.71	3
J-234	2	917.57	458.79	4
J-407	3	1594.84	531.61	5
J-737	3	1651.12	550.37	6
J-744	3	1891.61	630.54	7
J-666	2	1277.43	638.72	8
J-389	3	1918.27	639.42	9
J-256	3	2013.31	671.10	10
J-385	3	2208.93	736.31	11
J-225	3	2278.42	759.47	12
J-275	3	2371.33	790.44	13
J-224	3	2486.38	828.79	14
J-743	2	1683.76	841.88	15
J-265	3	2844.3	948.10	16
J-770	2	1976.45	988.23	17
J-58	3	3020.59	1006.86	18
J-264	3	3694.58	1231.53	19
J-218	3	4060.15	1353.38	20
J-133	3	4204.55	1401.52	21
J-185	3	4225.49	1408.50	22
J-132	3	4499.63	1499.88	23

B.6 Example Execution of Procedure on a Grid System

An example of the developed procedure for grid configured systems using KY 5 is outlined in this section.

1. Select ideal tank. Figure B.24 shows all four tanks that are possibilities for the ideal tank in KY 5. The list of criteria, along with the tank that was awarded a point for each criterion, is outlined below. Table B.4 shows the data for all tanks in the system, including the total number of points each tank was awarded in the tank selection process.

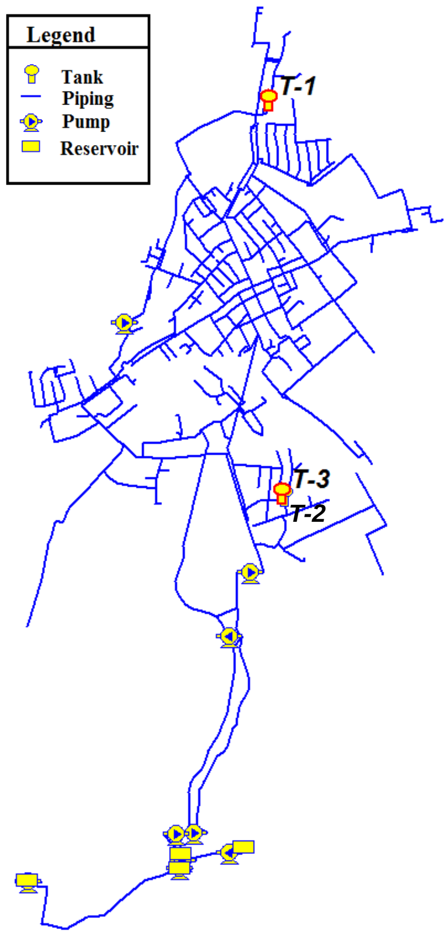


Figure B.24: Possible Ideal Tanks in KY 5.

1) Furthest downstream from the source/Water Treatment Plant: T-1

2) Lowest Hydraulic Grade Line (minimum water level in tanks): T-2 and T-3

3) Lowest Hydraulic Grade Line (maximum water level in tanks): T-2 and T-3

4) Lowest ground elevation: T-1

5) Smallest tank (by volume): T-1

6) Smallest pressure head (maximum water level – minimum water level): T-1

Table B.4: Tank Information and Point Total (KY 5).

Tank	Elev-ation (ft)	HGL (Max level - ft)	HGL (Min level -ft)	Pressure Head (ft)	Diameter (ft)	Volume (ft³)	Most Down-stream?	Located Interior?	Point Total
T-1	887.4	970	945	25	53	55155	Yes	Yes	4
T-2	901.4	960	925	35	68	127109	No	Yes	2
T-3	898.1	960	925	35	68	127109	No	Yes	2

It should be noted that the volume of tanks in the KYPIPE models were expressed as a fixed diameter. Therefore, the volume of the tanks was estimated using the equation for volume of a cylinder along with the fixed diameter and pressure head (maximum – minimum water level). If the volume of the tanks (in gallons) is known, these values should be used to determine the smallest tank by volume. T-1 was awarded five points total, while both T-2 and T-3 received two points each. Therefore, T-1 was selected as the ideal tank.

1a. Graphical Procedure. To find the optimal distance away from the ideal tank, T-1, to place a sensor, the total length of water lines in the system (in feet) along with the number of pumps in the system was used. The grid parameter, G, was calculated using Equation B-24. In this equation, α = 0.001.

$$G = \alpha\left(\frac{Total\ Length\ of\ Water\ Lines\ in\ System\ (ft)}{Number\ of\ Pumps^2}\right) = 0.001\left(\frac{316865\ ft}{9^2}\right) = 3.91 \quad \text{(B-24)}$$

The grid parameter, G, was then used in Equation B-25 in order to find the recommended distance from the ideal tank.

$$Distance\,(ft) = 311.14 \times e^{(0.0065\times 3.91)} = 319.15\ ft \quad \text{(B-25)}$$

The recommended distance from the ideal tank that a water quality sensor should be placed was found to be 319.15 feet, following the water lines. When looking at the configuration of KY 5, there is only one pipe connected to T-1. As the user attempts to find the node that is closest to the recommended distance away from T-1, it is obvious that J-321 should be selected. J-321 is located 400.66 feet away from T-1, and the recommended distance is 319.15 feet. This is the node located closest to T-1, so it is the obvious selection using the graphical procedure. The selected node is labeled in Figure B.25, along with the length of the water lines surrounding T-1.

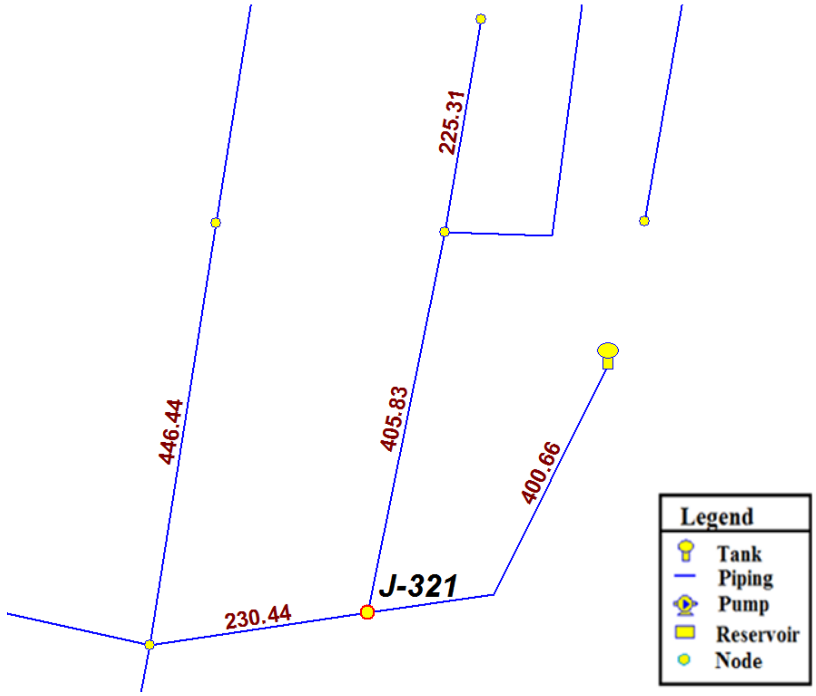


Figure B.25: Sensor Node Selection using the Graphical Procedure (KY 5).

If the user selected to execute the graphical procedure, the sensor placement guidance would now be complete.

2. Draw circle around ideal tank. The total length of pipes in KY 5 along with the approximate area the system covers was used to calculate the ideal radius. First, the system data was used to calculate the parameter R (Equation B-26).

$$R = \frac{Total\ Length\ of\ \ Pipes\ in\ System\ (ft)}{Approximate\ Area\ the\ System\ Covers\ (mi^2)} = \frac{316865\ ft}{6.1\ mi^2} = 51945.1 \qquad \text{(B-26)}$$

Because this value is between 50,000 and 60,000, an approximation of the ideal radius was 1500 feet (found with the provided ranges). A more exact calculation of the ideal radius was found using Equation B-27.

$$Radius = (-0.0494 \times R) + 4149.1 = (-0.0494 \times 51945.1) + 4149.1 = 1583.0\ \ ft \qquad \text{(B-27)}$$

Either value for the radius can be used. For this example, the approximation of 1500 feet was used. Because the ideal tank is not an exterior tank, it was not necessary to double the radius. A circle was drawn around the ideal tank using the calculated radius, with the tank at the center of the circle. This step is shown in Figure B.26. 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.

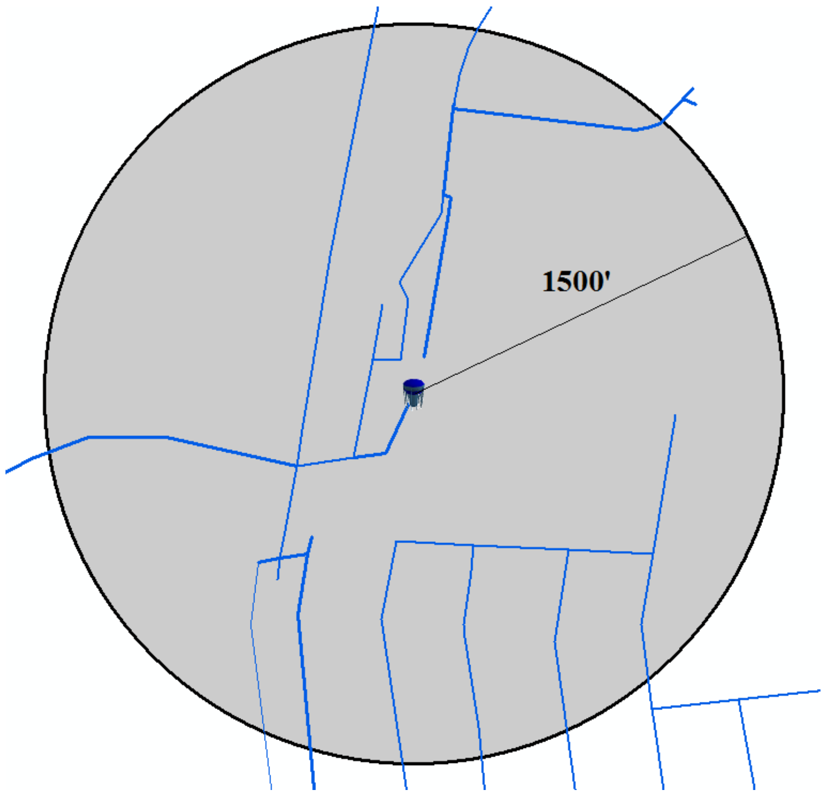


Figure B.26: Radius around Ideal Tank (KY 5).

3. Define all nodes located within circle. It should be noted that the procedure instructs the user to define nodes at locations where pipes intersect or where the pipe size/material changes. In the KYPIPE models used in this study, nodes are sometimes present at locations that do not fit these criteria. There is typically a demand present, but some nodes do not have a change of pipe size/material or intersect with other pipes. These nodes will be referred to as "phantom nodes". They will be included in the study and considered as possible sensor locations, but a typical utility manager carrying out this procedure would not include them. In this example illustrating KY 5, there are 14 nodes within the radius. If the "phantom nodes" are not included, there would only be 10 nodes listed as possible sensor locations. Figure B.27 displays the nodes located in the circle centered on the ideal tank in KY 5.

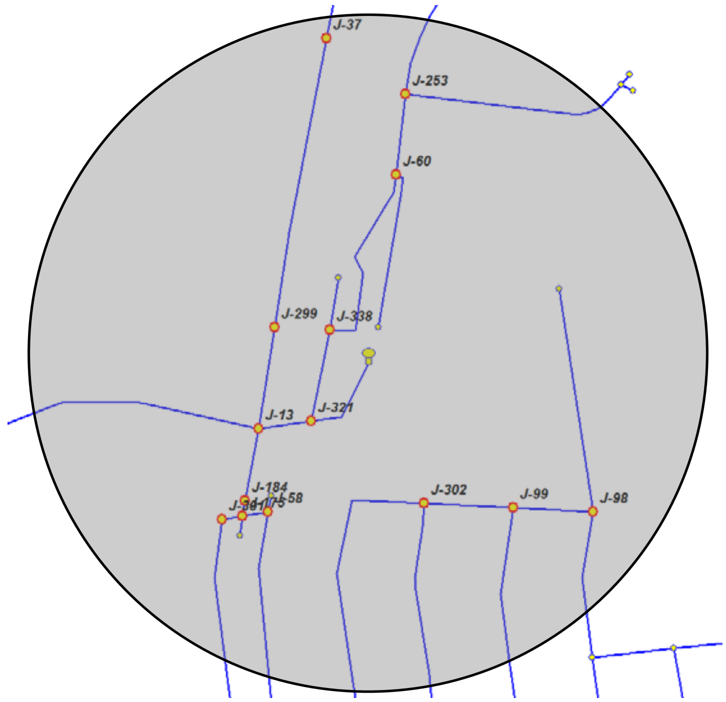


Figure B.27: Nodes Located in Circle (KY 5).

4. Collect data for each node in circle. For each potential sensor location defined in step #3, the distance from the ideal tank to the node (following the water lines) was calculated along with the number of pipes connected to the node (N_p). The value of Distance/ N_p was calculated for each node. This data is shown in Table B.5.

Table B.5: Data Collection for Nodes within Circle (KY 5).

Node	N_p	Distance (ft)	Distance / N_p
J-13	4	631.1	157.78
J-321	3	400.66	133.55
J-299	2	1077.54	538.77
J-37	2	2345.04	1172.52
J-253	3	1998.525	666.18
J-60	3	1650.75	550.25
J-338	3	806.49	268.83
J-175	4	1012.65	253.16
J-184	2	944.34	472.17
J-58	3	1125.06	375.02
J-301	2	1101.8	550.90
J-302	3	4629.24	1543.08
J-99	3	5013.2	1671.07
J-98	3	5358.1	1786.03

5. Rank the possible sensor locations. The nodes were ranking in terms of increasing values of the Distance/ N_p parameter. The node ranked first, with the lowest value of the parameter, is considered the ideal sensor location. If the ideal node is not suitable for the placement of a sensor, the ranked list can be used to find the next best location. The nodes within the circle ranked in terms of the best sensor locations can be seen in Table B.6. In KY 5, J-321 was the ideal location for a water quality sensor.

Table B.6: Ranked Nodes (KY 5).

Node	N_p	Distance (ft)	Distance / N_p	Ranking
J-321	3	400.66	133.55	1
J-13	4	631.1	157.78	2
J-175	4	1012.65	253.16	3
J-338	3	806.49	268.83	4
J-58	3	1125.06	375.02	5
J-184	2	944.34	472.17	6
J-299	2	1077.54	538.77	7
J-60	3	1650.75	550.25	8
J-301	2	1101.8	550.90	9
J-253	3	1998.525	666.18	10
J-37	2	2345.04	1172.52	11
J-302	3	4629.24	1543.08	12
J-99	3	5013.2	1671.07	13
J-98	3	5358.1	1786.03	14

B.7 Example Execution of Procedure on a Branch System

An example of this procedure for branch configured systems using KY 9 is outlined in this section. The system contains 15 storage tanks. Because there are less than 20 tanks, the procedure can be used to recommend sensor placement.

1. Select ideal tank.

A. Draw a circle around the entire system, ensuring it is the smallest possible circle while still including all components. The center of the circle is located and the radius is measured. This step is shown in Figure B.28. The radius was measured to be 81055 feet. The measurement tool in GIS was used to find the length of the radius, but a scaled map and ruler would also be sufficient.

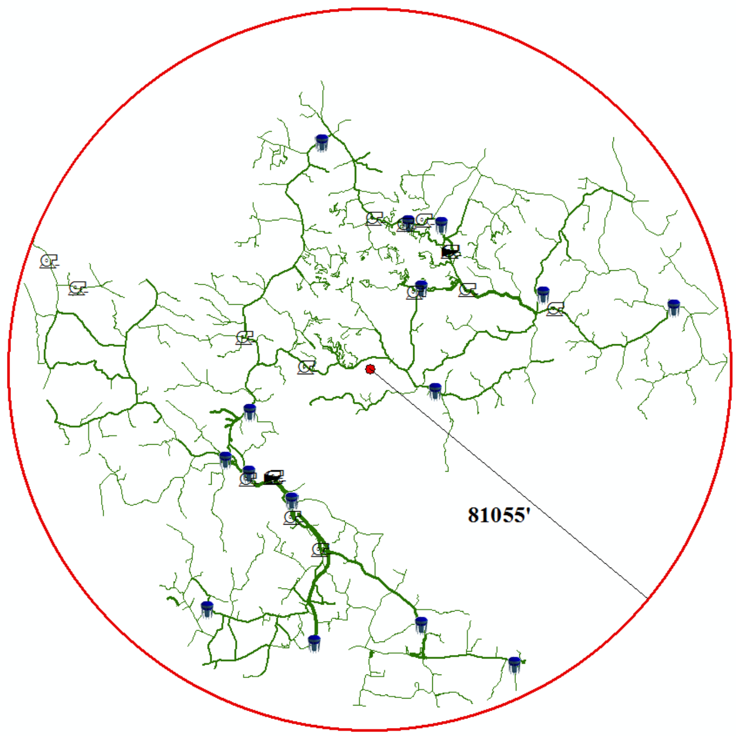


Figure B.28: Example of Circle Around Entire System (KY 9).

Next, the parameter P was calculated using information about the total length of water lines in the system and the length of the radius. This is shown in Equation B-28.

$$P = \frac{\textit{Total Length of Water Lines in System (ft)}}{\textit{Radius of Large Circle to Cover Entire System (ft)}} = \frac{3155866.4 \ ft}{81055 \ ft} = 38.93 \quad \text{(B-28)}$$

The value for P was used to find the percentage of the large radius needed for the small radius (Equation B-29). This percentage (already in decimal form, so it was not necessary to divide this value by 100) was multiplied by the large radius to find the value for the small radius (Equation B-30).

$$Percentage = (-0.0086 \times P) + 0.715 = (-0.0086 \times 38.93) + 0.715 = 0.38 \quad \text{(B-29)}$$

$$Small\ Radius\ (ft) = Percentage \times Large\ Radius\ (ft) = 0.38(81055\ \ ft) = 30800.9\ \ ft \quad \text{(B-30)}$$

The small radius was drawn around the center of the large circle using the calculated radius. Figure B.29 shows this step in the ideal tank selection process.

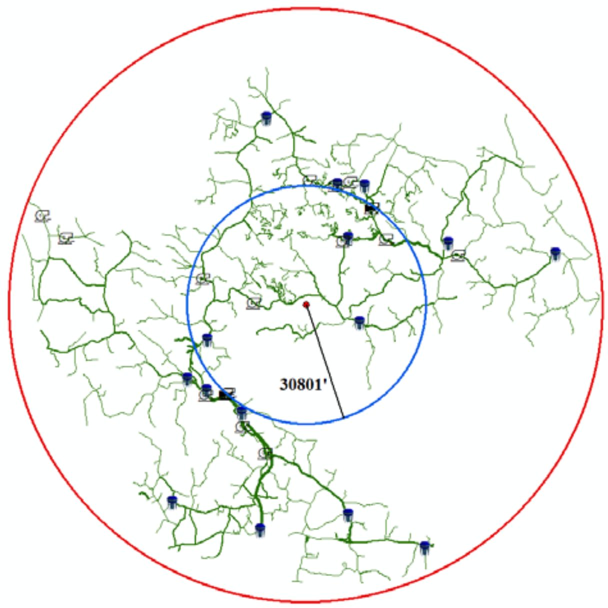


Figure B.29: Example of Ideal Tank Selection Process (KY 9).

Out of the 15 tanks in the system, only three tanks are located within the smaller circle. Therefore, these three tanks were the only tanks considered as possibilities for the ideal tank. Figure B.30 shows all three tanks that are possibilities for the ideal tank in KY 9. The list of criteria, along with the tank that was awarded a point for each criterion, is outlined below. Table B.7 displays data for the three possible ideal tanks (data for the remainder of the tanks is excluded), including the total number of points each tank was awarded in the ideal tank selection process.

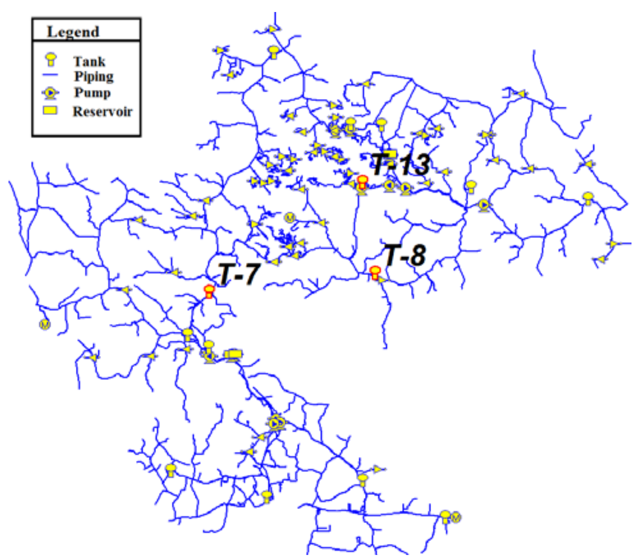


Figure B.30: Potential Ideal Tanks in KY 9.

1) Lowest ground elevation: T-13

2) Lowest Hydraulic Grade Line (looking at minimum water level in tanks): T-13

3) Lowest Hydraulic Grade Line (looking at maximum water level in tanks): T-13

4) Located within 2000 feet of a pump: T-13

5) Located in a downtown area: Not applicable

Table B.7: Tank Information and Point Total (KY 9)

Tank	Elevation (ft)	HGL (Max level - ft)	HGL (Min level -ft)	Diameter (ft)	Volume (ft^3)	Located in Downtown Area?	Point Total
T-7	757.9	865	850	16	3016	No	0
T-8	825.6	1045	1000	27	25765	No	0
T-13	724.2	825	805	20	6283	No	4

T-13 was awarded four points total, while both T-2 and T-3 did not receive any points. Therefore, T-13 was selected as the ideal tank.

1a. Graphical Procedure. To find the optimal distance away from the ideal tank (identified in step 1) to place a sensor, specific information about the network is needed. First, the average length of water lines in the system (in feet) is required, found by dividing the total length of all pipelines in the system by the total number of pipes present. The area of the circle needed to encompass the entire system (drawn in step 1 during the tank selection process) is also needed. Because only the radius of the large circle was measured in step 1, Equation B-31 was first used to calculate the area of the circle.

$$A\,(mile^2) = \pi \times R^2 = \pi \times (15.35\ mi)^2 = 740.4\ mi^2 \qquad \text{(B-31)}$$

where A represents the area of the circle to encompass the entire system (mi^2) and R is the radius of this circle (mi). The branch parameter, B, was then calculated using Equation B-32.

$$B = \frac{Area\ of\ Circle\ to\ Cover\ System\ (mi^2)}{Average\ Pipe\ Length\ (mi)} = \frac{740.4\ mi^2}{2504.7\ ft \times \frac{1\ mile}{5280\ ft}} = 1560.8 \qquad \text{(B-32)}$$

The branch parameter, B, was then used in Equation B-33 in order to find the recommended distance from the tank.

$$Distance\,(ft) = 40.705 \times e^{(0.0015 \times 1560.8)} = 423.01\ ft \qquad \text{(B-33)}$$

423.01 feet is the recommended distance from the ideal tank that a water quality sensor should be placed, following the water lines. When looking at the configuration of KY 9, there is a node located 226.48 feet away from T-13. There is a pump located 643.35 feet from the tank to the west, but the procedure states that the sensor should not be placed at a pump. The next closest node is located 2260.24 feet to the east of the tank. It is clear that the node located closest to the recommended distance is J-708, located 226.48 feet away from T-13. The selected node is labeled in Figure B.31, along with the lengths of the pipes near T-13.

Figure B.31: Sensor Node Selection using the Graphical Procedure (KY 9).

2. Draw circle around ideal tank. The area of the circle needed to cover the entire network (drawn in the ideal tank selection process) was used to calculate the ideal radius. First, the measured radius of the circle was used to calculate the area (Equation B-34). The radius was originally measured in feet, so this value was divided by 5280 to find the radius (R) in miles. 81055 feet converted to 15.35 miles.

$$A\,(mi^2) = \pi \times R^2 = \pi \times (15.35\ mi)^2 = 740.36\ mi^2 \qquad \text{(B-34)}$$

where A represents the area of the circle to encompass the entire system (mi^2) and R is the radius of this circle (mi). The area of the circle (in square miles) was then used to calculate the radius of the circle (in feet) around the ideal tank. This is shown in Equation B-35.

$$Radius\ (ft) = (7.9892A) + 755.88 = (7.9892 \times 740.36\ mi^2) + 755.88 = 6670.8\,ft \quad \text{(B-35)}$$

For this example, the approximation of 6500 feet was used for the radius. Because the ideal tank was not located in a downtown area, it was not necessary to divide the radius by five. A circle was drawn around the ideal tank using the calculated radius, with the tank at the center of the circle. This step is shown in Figure B.32. 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.

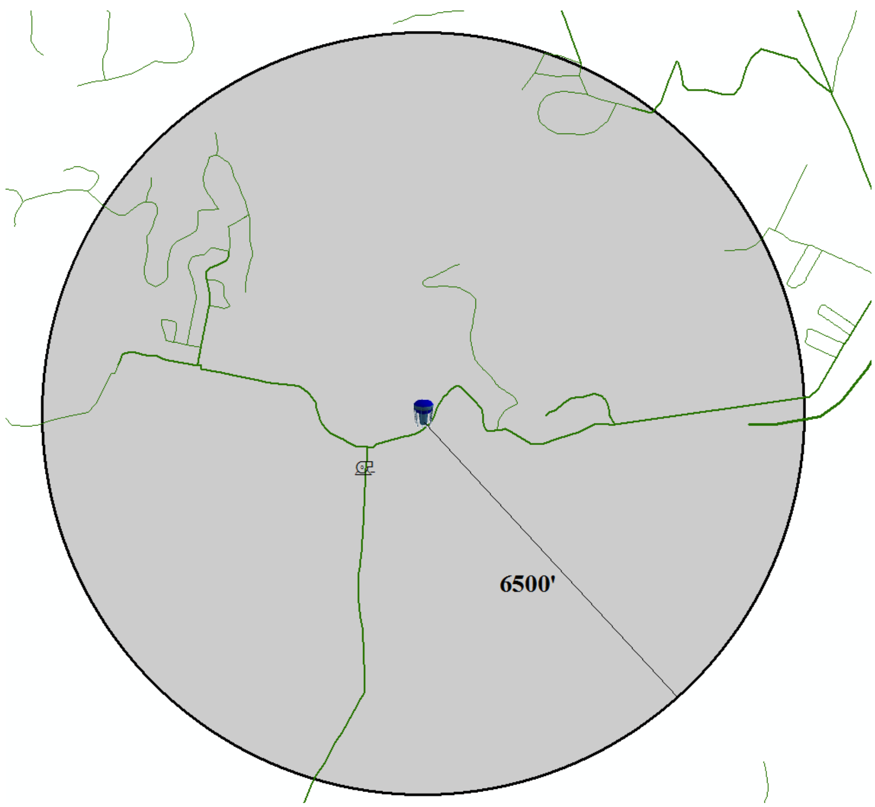


Figure B.32: Radius around Ideal Tank (KY 9).

3. Define all nodes located within circle. It should be noted that the procedure instructs the user to define nodes at locations where pipes intersect or where the pipe size/material changes. In the KYPIPE models used in this study, nodes are sometimes presents at locations that do not fit these criteria. There is typically a demand present, but some nodes do not have a change of pipe size/material or intersect with other pipes. These nodes will be referred to as "phantom nodes". They will be included in the study and considered as possible sensor locations, but it would not be necessary for a typical utility manager carrying out this procedure to include them. In this example illustrating KY 9, there are 21 nodes within the radius. If the "phantom nodes" are not included, there would be 20 nodes listed as possible sensor locations. Figure B.33 displays the nodes located within the circle centered on the ideal tank in KY 9.

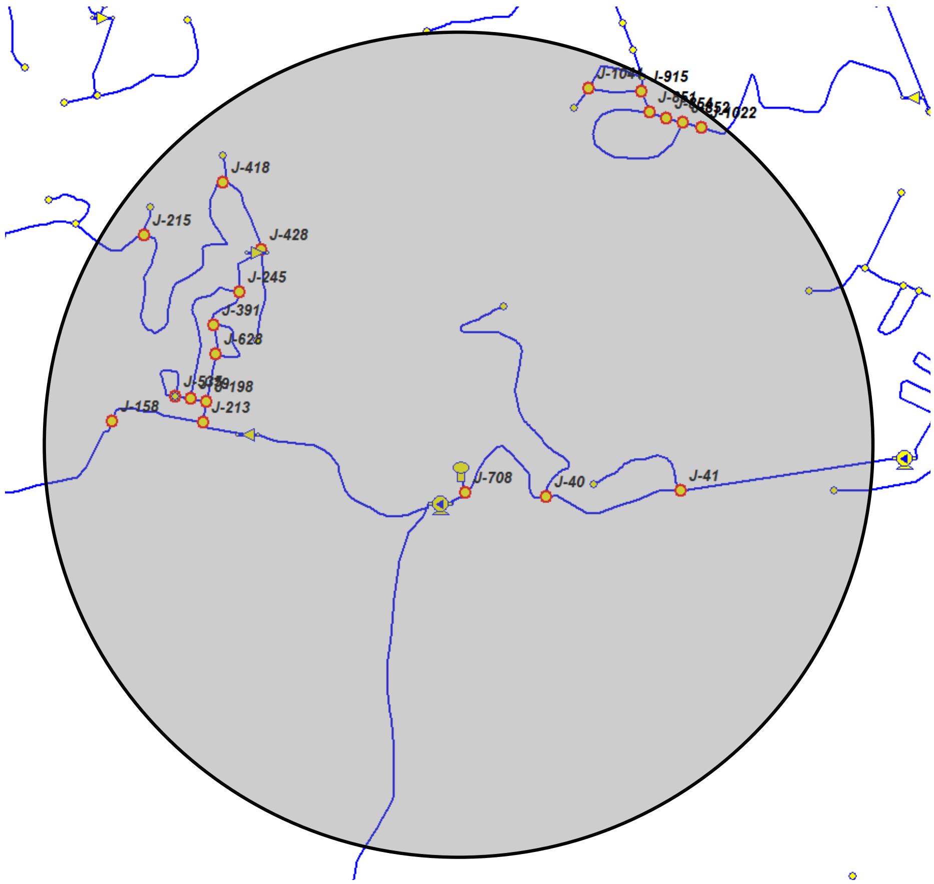


Figure B.33: Nodes Located in Circle (KY 9).

4. Collect data for each node in circle. For each node defined as a potential sensor location, the distance from the ideal tank to the node (following the water lines) was calculated along with the number of pipes connected to the node (N_p). The value of Distance/ N_p was calculated for each node. This data is shown in Table B.8.

Table B.8: Data Collection for Nodes within Circle (KY 9).

Node	N_p	Distance (ft)	Distance / N_p
J-40	3	2260.24	753.41
J-1022	2	20109.39	10054.70
J-1041	3	22038.25	7346.08
J-158	2	6324.32	3162.16
J-198	3	5138.03	1712.68
J-213	3	4822.94	1607.65
J-215	3	13837.34	4612.45
J-245	3	7009.13	2336.38
J-391	3	6297.56	2099.19
J-41	3	4407.69	1469.23
J-418	3	9042.25	3014.08
J-428	3	7825.15	2608.38
J-628	3	5857.65	1952.55
J-708	3	226.48	75.49
J-79	3	5385.68	1795.23
J-80	3	5605.31	1868.44
J-851	3	20924.17	6974.72
J-852	3	20395.95	6798.65
J-854	2	20654.37	10327.19
J-915	3	21256.78	7085.59

5. Rank the possible sensor locations. The nodes were ranking in terms of increasing values of the Distance/ N_p parameter. The node ranked first, with the lowest value of the parameter, is considered the ideal sensor location. If the ideal node is not suitable for the placement of a sensor, the ranked list can be used to find the next best location. The nodes within the circle ranked in terms of the best sensor locations can be seen in Table B.9. In this example illustrating the KY 9 network, J-708 was determined to be the ideal location for placement of a water quality sensor.

Table B.9: Ranked Nodes (KY 9).

Node	N_p	Distance (ft)	Distance / N_p	Ranking
J-708	3	226.48	75.49	1
J-40	3	2260.24	753.41	2
J-41	3	4407.69	1469.23	3
J-213	3	4822.94	1607.65	4
J-198	3	5138.03	1712.68	5
J-79	3	5385.68	1795.23	6
J-80	3	5605.31	1868.44	7
J-628	3	5857.65	1952.55	8
J-391	3	6297.56	2099.19	9
J-245	3	7009.13	2336.38	10
J-428	3	7825.15	2608.38	11
J-418	3	9042.25	3014.08	12
J-158	2	6324.32	3162.16	13
J-215	3	13837.34	4612.45	14
J-852	3	20395.95	6798.65	15
J-851	3	20924.17	6974.72	16
J-915	3	21256.78	7085.59	17
J-1041	3	22038.25	7346.08	18
J-1022	2	20109.39	10054.70	19
J-854	2	20654.37	10327.19	20

Appendix C

Execution of Sensor Placement Procedure on Verification Systems

C.1 Verification of Loop System

KY 13 was developed as the model for verification of the loop configured systems. The general configuration and major system components of KY 13 are displayed in Figure C.1.

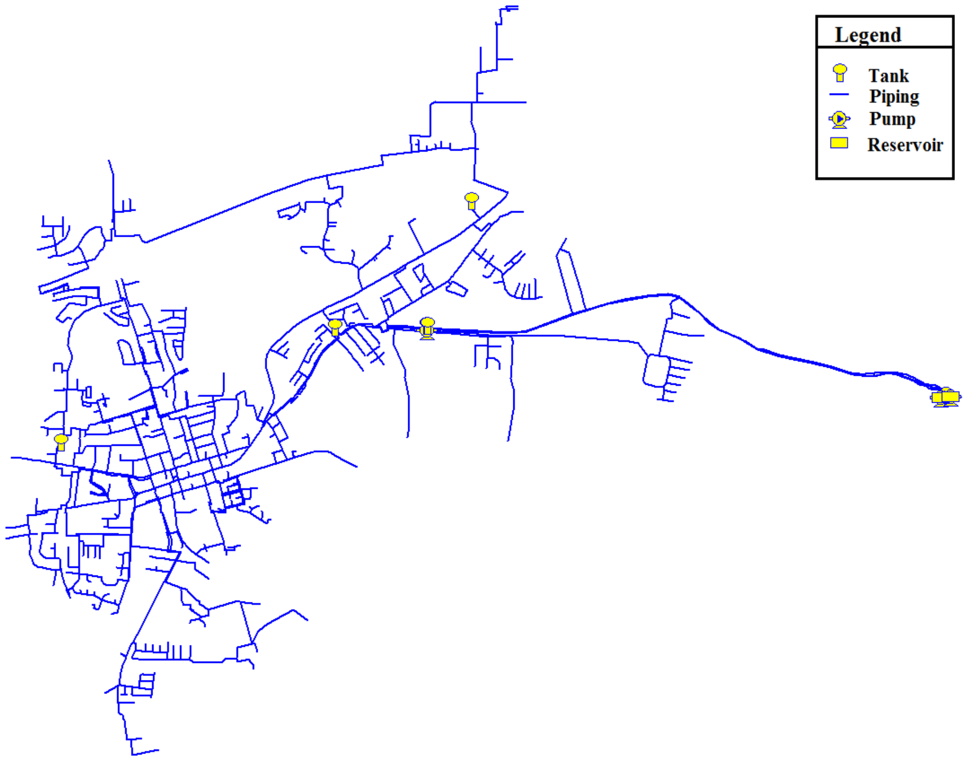


Figure C.1: General Configuration of KY 13.

The entire process for sensor placement guidance is outlined in this section, including both the graphical method and the full five step simplified procedure.

1. Select the ideal tank. All five storage tanks in the system are considered candidates for the ideal tank.

1) Furthest downstream from the source/Water Treatment Plant without being located on the exterior of the system (see Figure C.2): T-5

Figure C.2: Ideal Tank Selection (KY 13).

2) Lowest Hydraulic Grade Line (looking at minimum water level in tanks): T-5

3) Lowest Hydraulic Grade Line (looking at maximum water level in tanks): T-5

4) Lowest ground elevation: T-1

5) Smallest (by volume): T-4

Table C.1: Tank Data and Point Totals (KY 13).

Tank	Elevation (ft)	HGL (Max level - ft)	HGL (Min level -ft)	Diameter (ft)	Volume (ft^3)	Most Down-stream?	Located Interior?	Point Total
T-1	1018.7	1152	1124	123.27	334166	No	Yes	1
T-2	1019.6	1153	1125	123.27	334166	No	Yes	0
T-3	1023	1174	1154	65.23	66837	No	Yes	0
T-4	1029.8	1174	1156	53.26	40102	No	Yes	1
T-5	1044.8	1142	1122	65.23	66837	Yes	Yes	3

The point total for the ideal tank selection step is shown in Table C.1, along with relevant data for all tanks in the system. T-5 was selected as the ideal tank.

1a. Graphical Procedure. To find the optimal distance away from the ideal tank (identified in step 1) to place a sensor, the total length of water lines in the system (in feet) along with the number of tanks in the system was used. The loop parameter, L, shown in Equation C-1 was calculated. In this equation, α = 0.001.

$$L = \alpha\left(\frac{Total\ Length\ of\ Water\ Lines\ in\ System\ (ft)}{Number\ of\ Tanks^2}\right) = 0.001\left(\frac{492917.3\,ft}{5^2}\right) = 19.72 \quad \text{(C-1)}$$

The loop parameter, L, should then be used in Equation C-2 in order to find the recommended distance from the tank.

$$Distance\,(ft) = 28.765 \times e^{(0.0654 \times L)} = 28.765 \times e^{(0.0654 \times 19.72)} = 104.44\ ft \qquad \text{(C-2)}$$

104.44 feet is the recommended distance from the ideal tank that a water quality sensor should be placed, following the water lines. T-5 was selected as the ideal tank in KY 13, and the node closest to this tank (J-516) is located 129.85 feet away from the tank. Because J-516 is the closest to the tank, and it is already slightly further away than the recommended distance, this node is the obvious choice for a sensor location using the graphical procedure. The selected node is labeled in Figure C.3, along with the length of the water lines near T-5.

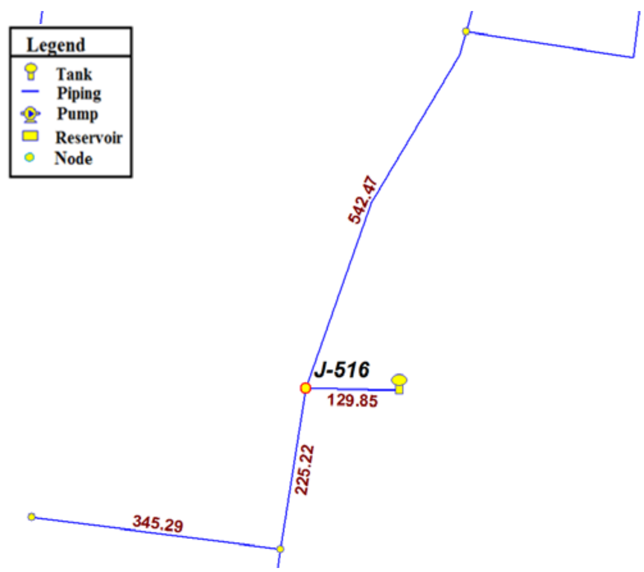


Figure C.3: Sensor Node Selection using the Graphical Procedure (KY 13).

2. Draw circle around ideal tank. Equation C-3 is used to determine the necessary radius of the circle.

$$R = \frac{Total\ \ Length\ of\ \ Water\ \ Lines\ in\ System\ (\ ft)}{Approximate\ \ Area\ the\ System\ Covers\ (mi^2)} = \frac{492917.3\ \ ft}{11.2\ mi^2} = 44121.6 \qquad \text{(C-3)}$$

The calculated parameter R was then used to find the required radius based on a set of ranges. Because the value was between 40,000 and 50,000, the approximate radius was 2000 feet. Alternatively, an equation can be used to find a more exact value for the radius around the ideal tank. The calculate parameter R can be used in Equation C-4 to find the required radius.

$$Radius\ (\ ft) = (-0.0494 \times R) + 4149.1 = (-0.0494 \times 44121.6) + 4149.1 = 1969.5\ \ ft \qquad \text{(C-4)}$$

The ideal tank was not located on the exterior of the system, so the radius did not need to be doubled. For the verification study, the approximate radius of 2000 feet was used. The circle drawn around the ideal tank can be seen in Figure C.4. 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.

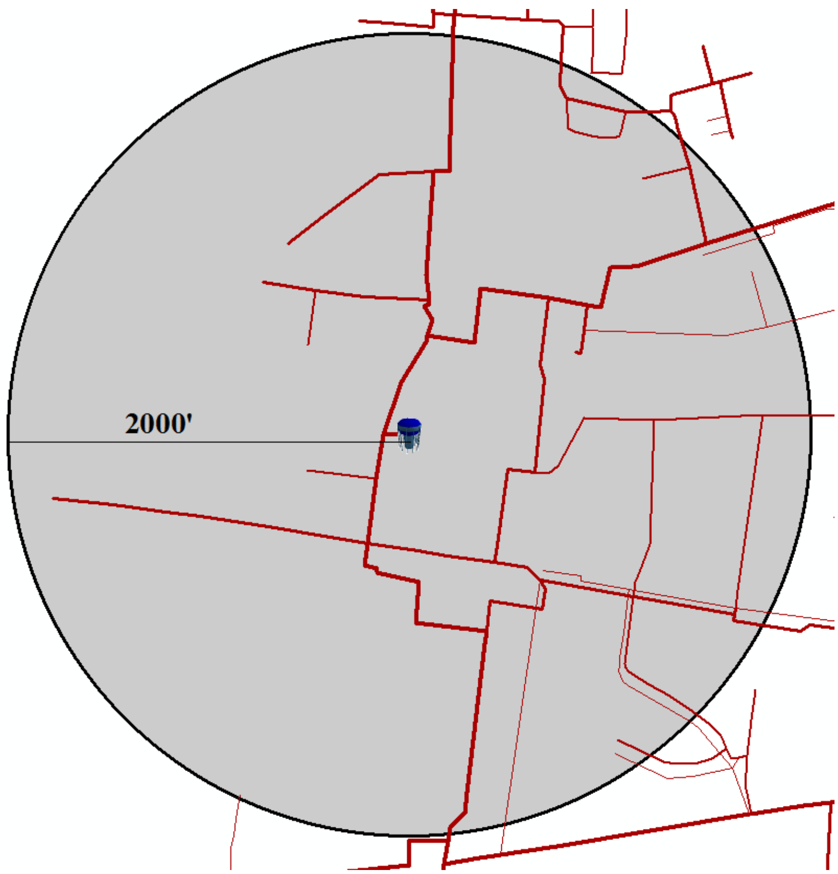


Figure C.4: Circle around Ideal Tank (KY 13).

3. Define all nodes within the circle. This list of nodes will act as possible sensor locations. All nodes that were present in the KYPIPE model and are located within the circle drawn around the ideal tank are included in the list of potential sensor locations. These nodes are shown in Figure C.5.

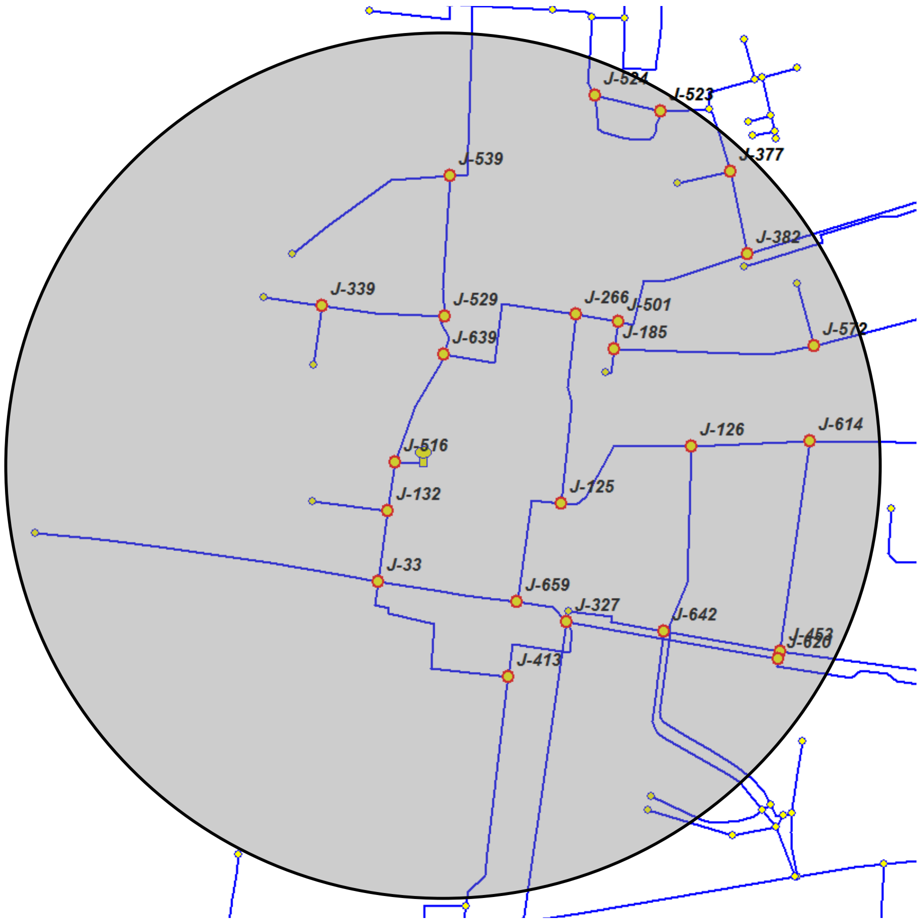


Figure C.5: Nodes within Circle around Ideal Tank (KY 13).

4. Collect data for each node in the circle. Two parameters were collected for all nodes defined in the previous step: the number of pipes connected to the node (N_p) and the distance from the ideal tank following the water lines (in feet). For each node, the Distance/ N_p parameter was also calculated. This data can be viewed in Table C.2.

Table C.2: Data Collection for Nodes within Circle (KY 13).

Node	N_p	Distance (ft)	Distance / N_p
J-125	3	1924.98	641.66
J-126	3	2674.94	891.65
J-132	3	355.07	118.36
J-185	3	1838.39	612.80
J-266	3	1516.91	505.64
J-327	4	1577.48	394.37
J-33	4	678.96	169.74
J-339	3	1448.69	482.90
J-377	3	2872.63	957.54
J-382	3	2486.85	828.95
J-413	3	1654.62	551.54
J-453	4	2593	648.25
J-501	3	1713.75	571.25
J-516	3	129.85	43.28
J-523	3	3394.89	1131.63
J-524	3	3702.31	1234.10
J-529	3	881.26	293.75
J-539	3	1525.08	508.36
J-572	3	2752.53	917.51
J-614	3	3217.18	1072.39
J-620	3	2558.95	852.98
J-639	3	672.32	224.11
J-642	3	3131.52	1043.84
J-659	3	1320.48	440.16

5. Rank the possible sensor locations. The set of nodes within the circle was ranked from the lowest value of Distance/ N_p to the highest value. The node ranked first (lowest value) is considered the optimal sensor location. Excel was used for this procedure, and the data is shown in Table C.3. For the KY 13 system used for verification purposes, J-516 was selected as the ideal node because it had the lowest value of Distance/ N_p.

Table C.3: Ranked Nodes (KY 13).

Node	N_p	Distance (ft)	Distance / N_p	Ranking
J-516	3	129.85	43.28	1
J-132	3	355.07	118.36	2
J-33	4	678.96	169.74	3
J-639	3	672.32	224.11	4
J-529	3	881.26	293.75	5
J-327	4	1577.48	394.37	6
J-659	3	1320.48	440.16	7
J-339	3	1448.69	482.90	8
J-266	3	1516.91	505.64	9
J-539	3	1525.08	508.36	10
J-413	3	1654.62	551.54	11
J-501	3	1713.75	571.25	12
J-185	3	1838.39	612.80	13
J-125	3	1924.98	641.66	14
J-453	4	2593	648.25	15
J-382	3	2486.85	828.95	16
J-620	3	2558.95	852.98	17
J-126	3	2674.94	891.65	18
J-572	3	2752.53	917.51	19
J-377	3	2872.63	957.54	20
J-642	3	3131.52	1043.84	21
J-614	3	3217.18	1072.39	22
J-523	3	3394.89	1131.63	23
J-524	3	3702.31	1234.10	24

C.2 Verification of Grid System

KY 14 was developed as the verification model for the grid configured systems. The general configuration and major system components of KY 14 are displayed in Figure C.6. The procedure developed for sensor placement in grid systems is outlined.

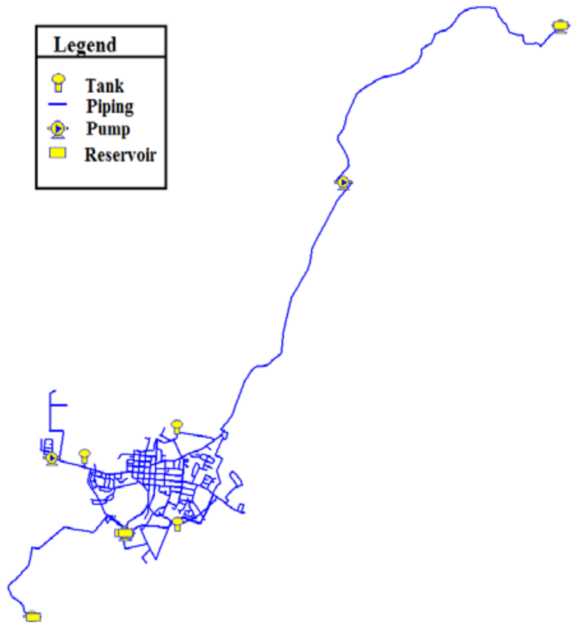


Figure C.6: General Configuration of KY 14.

1. Select the ideal tank. Because the system has less than five tanks, the preliminary step is not necessary. All three tanks in the system are considered possibilities for the ideal tank. The criteria for tank selection, along with the tanks that received points for each criterion, are outlined below and data is displayed in Table C.4.

1) Furthest downstream from the source/Water Treatment Plant (see Figure C.7): T-3

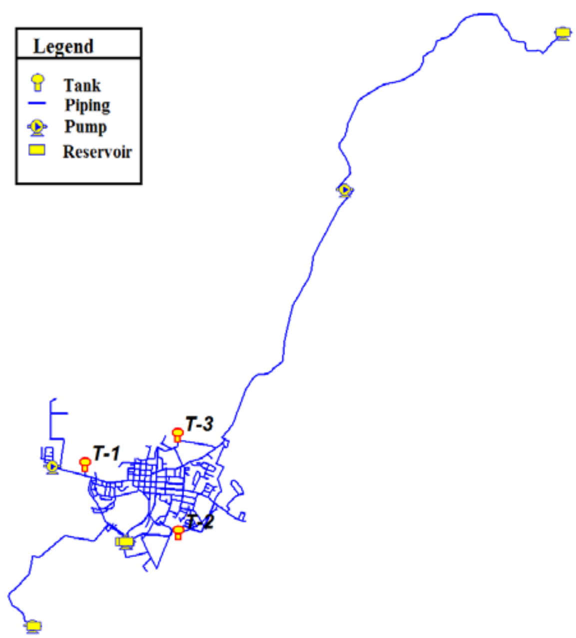


Figure C.7: Ideal Tank Selection (KY 14).

A. Lowest Hydraulic Grade Line (minimum water level in tanks): T-3

B. Lowest Hydraulic Grade Line (maximum water level in tanks): T-3

C. Lowest ground elevation: T-3

D. Smallest (by volume): T-3

E. Smallest pressure head (maximum water level in tank – minimum water level): T-1 and T-3

Table C.4: Tank Data and Point Totals (KY 14).

Tank	Elevation (ft)	HGL (Max level - ft)	HGL (Min level -ft)	Pressure Head (ft)	Diameter (ft)	Volume (ft^3)	Most Down-stream?	Located Interior ?	Point Total
T-1	839.0	945	926	19	66.93	66847	Maybe	No	1
T-2	847.3	950	930	20	92.48	134343	No	No	0
T-3	806.8	941	922	19	51.84	40103	Yes	No	6

T-3 received the highest number of points. Therefore, T-3 was selected as the ideal tank.

1a. Graphical Procedure. To find the optimal distance away from the ideal tank (T-3) to place a sensor, the total length of water lines in the system (in feet) along with the number of pumps in the system was used. The grid parameter, G, was calculated using Equation C-5. In this equation, $\alpha = 0.001$.

$$G = \alpha\left(\frac{Total\ Length\ of\ Water\ Lines\ in\ System\ (ft)}{Number\ of\ Pumps^2}\right) = 0.001\left(\frac{340429.4\ ft}{6^2}\right) = 9.46 \quad \text{(C-5)}$$

The grid parameter, G, was then used in Equation C-6 in order to find the recommended distance from the tank.

$$Distance\,(ft) = 311.14 \times e^{(0.0065 \times 9.46)} = 330.86\ ft \quad \text{(C-6)}$$

The recommended distance from the ideal tank that a water quality sensor should be placed was calculated to be 330.86 feet, following the water lines. When looking at the configuration of KY 14, there is a node located 86.45 feet away from T-3. There is also a node located 183.25 feet away. However, this is a dead-end node so it is not eligible for sensor placement. The next closest node is located 770.15 feet from the ideal tank. Because the goal is to select the node that is closest to the recommended distance away from the tank, the node that is located 183.25 feet from T-3 is nearest the recommended distance of 330.86 feet. Therefore, J-136 is selected as the ideal sensor node using the graphical procedure. The selected node is labeled in Figure C.8, along with the length of the water lines near T-3.

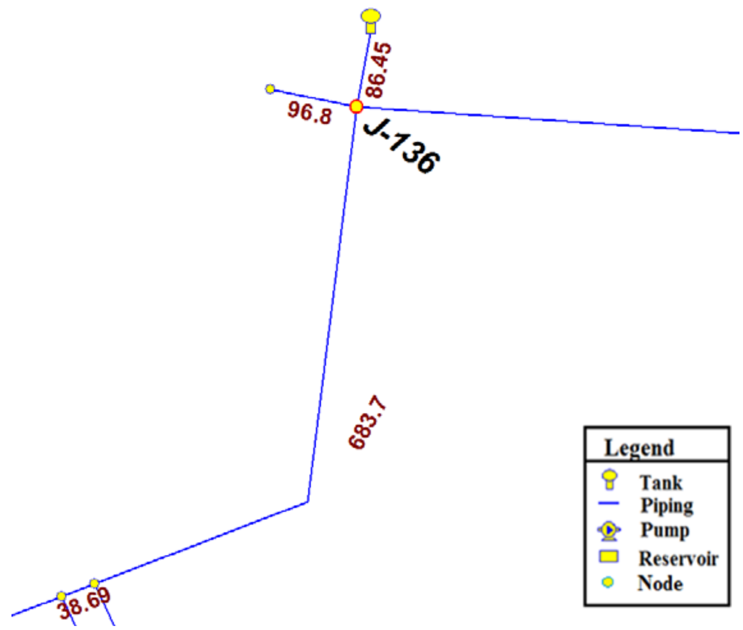


Figure C.8: Sensor Node Selection using the Graphical Procedure (KY 14).

2. Draw circle around ideal tank. An equation was used to determine the necessary radius of the circle. The total length of pipelines in the system and the approximate area of the system were used to calculate the parameter R, shown in Equation C-7.

$$R = \frac{Total\ \ Length\ of\ \ Water\ Lines\ in\ System\ (\ ft)}{Approximate\ \ Area\ the\ System\ Covers\ (mi^2)} = \frac{340429.4\ \ ft}{5.6\ mi^2} = 60791.0 \qquad \text{(C-7)}$$

The calculated parameter R was then used to find the required radius based on a set of ranges. Because the parameter was greater than 60000, the required radius was 1000 feet. However, the ideal tank was located on the exterior of the system, so the radius was doubled to 2000 feet. Alternatively, an equation can be used to find a more exact value for the radius around the ideal tank. The calculated parameter R was used in Equation C-8 to find the required radius (the entire equation was multiplied by two because the tank was located on the exterior of the system).

$$Radius = 2[(-0.0494 \times R) + 4149.1] = 2[(-0.0494 \times 60791.0) + 4149.1] = 2303.7\ \ ft \quad \text{(C-8)}$$

For simplicity, the approximate radius of 2000 feet was used. A circle with the calculated radius was drawn around the ideal tank, 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. This is shown in Figure C.9.

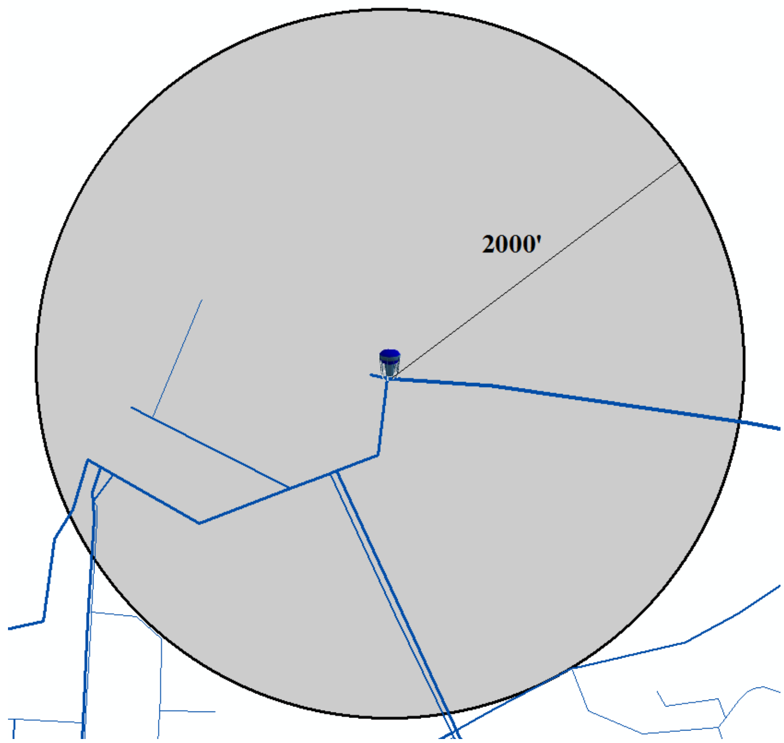


Figure C.9: Circle around Ideal Tank (KY 14).

3. Define all nodes within the circle. When the list of nodes within the circle was compiled, there were only eight nodes located within the circle. Because there were not at least 10 nodes in the list of possible sensor locations, the radius was increased by 500 feet. After the radius was increased, there were 17 nodes present within the circle. The new radius is shown in Figure C.10, and all nodes located within the radius are shown in Figure C.11.

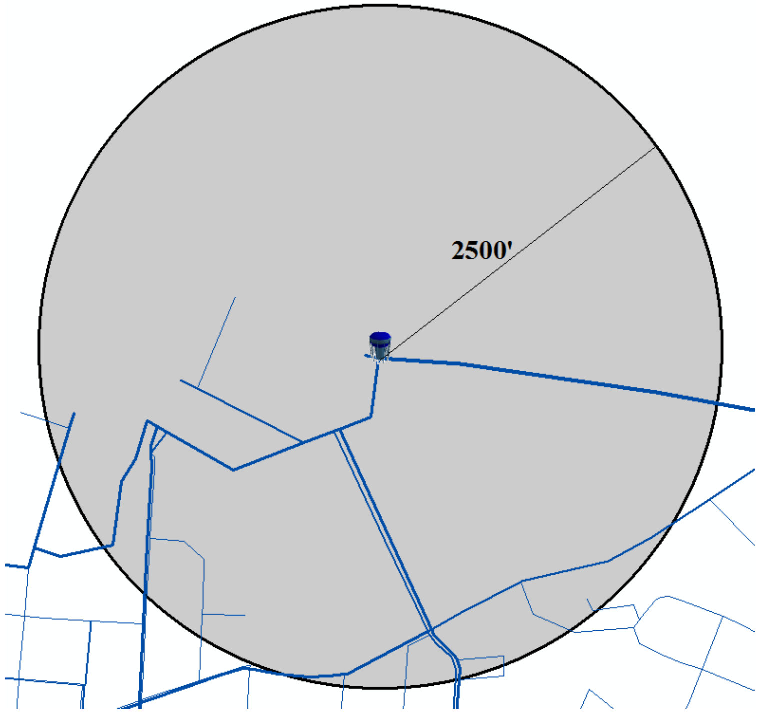


Figure C.10: Updated Circle around Ideal Tank (KY 14).

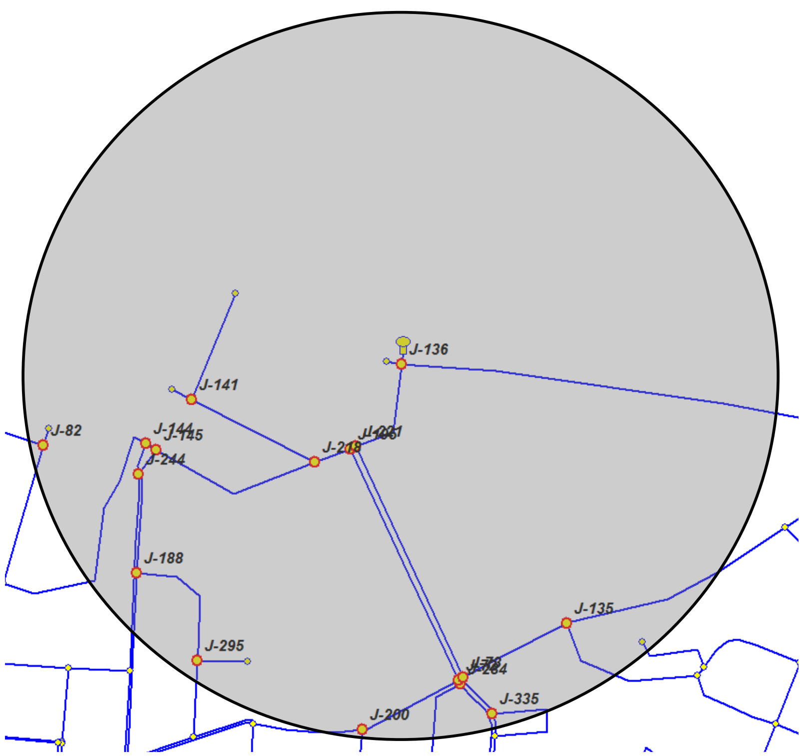


Figure C.11: Nodes within Circle around Ideal Tank (KY 14).

4. Collect data for each node in the circle. Two parameters were needed for each node within the circle: the shortest distance from the node to the ideal tank following the water lines (in feet) and the number of pipes connected to the node (N_p). For each node, the Distance/ N_p parameter was calculated. This data is displayed in Table C.5.

Table C.5: Data Collection of Nodes (KY 14).

Node	N_p	Distance (ft)	Distance / N_p
J-135	3	3135.62	1045.21
J-136	4	86.45	21.61
J-141	3	1925.09	641.70
J-144	3	2240.47	746.82
J-145	3	2160.91	720.30
J-188	3	2986.94	995.65
J-195	3	808.84	269.61
J-200	3	3112.14	1037.38
J-218	3	1050.02	350.01
J-221	3	770.15	256.72
J-244	4	2352.24	588.06
J-284	3	2454.39	818.13
J-295	3	3836.66	1278.89
J-335	3	2691.89	897.30
J-72	4	2424.64	606.16
J-73	4	2395.14	598.79
J-82	3	4796.12	1598.71

5. Rank the possible sensor locations. The set of nodes within the circle was ranked from the lowest value of Distance/ N_p to the highest value. The node ranked first (lowest value) is considered the optimal sensor location. The “Sort” tool in Excel was used to rank the data from highest to lowest. However, this step can also be completed by hand. Using the methodology developed in this study, J-136 was ranked as the best location for placement of a sensor. The full set of nodes and their rankings are shown in Table C.6.

Table C.6: Ranked Nodes (KY 14).

Node	N_p	Distance (ft)	Distance / N_p	Ranking
J-136	4	86.45	21.61	1
J-221	3	770.15	256.72	2
J-195	3	808.84	269.61	3
J-218	3	1050.02	350.01	4
J-244	4	2352.24	588.06	5
J-73	4	2395.14	598.79	6
J-72	4	2424.64	606.16	7
J-141	3	1925.09	641.70	8
J-145	3	2160.91	720.30	9
J-144	3	2240.47	746.82	10
J-284	3	2454.39	818.13	11
J-335	3	2691.89	897.30	12
J-188	3	2986.94	995.65	13
J-200	3	3112.14	1037.38	14
J-135	3	3135.62	1045.21	15
J-295	3	3836.66	1278.89	16
J-82	3	4796.12	1598.71	17

C.3 Verification of Branch System

KY 15 was developed as the verification model for the branch systems. The general configuration and major system components of KY 15 are displayed in Figure C.12.

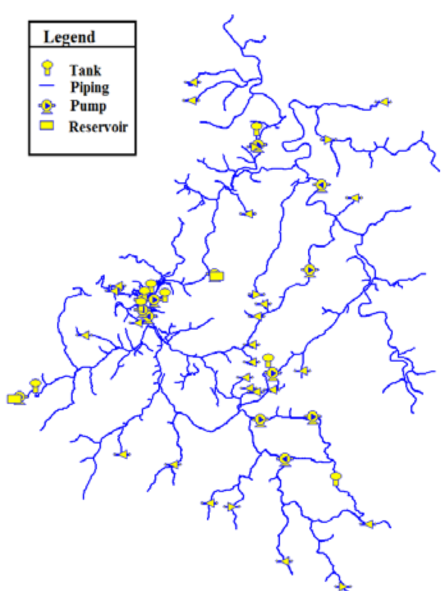


Figure C.12: General Configuration of KY 15.

The procedure for sensor placement in branch systems is outlined below. The water distribution system in KY 15 contains eight storage tanks. Because the network has less than 20 storage tanks, the procedure outline below can be used.

1. Select the ideal tank.

A. A circle was drawn around the entire system, ensuring it was the smallest possible circle while still including all components. The center of the circle was marked, and the radius was measured. Next, a smaller circle was drawn around the center of the large circle. To calculate the required radius for the smaller circle, the total length of pipelines in the system along with the radius of the large circle was needed. This information was used to calculate the parameter P shown in Equation C-9.

$$P = \frac{\text{Total Length of Water Lines in System (ft)}}{\text{Radius of Large Circle to Cover Entire System (ft)}} = \frac{1581482.3\ ft}{69305\ ft} = 22.82 \quad \text{(C-9)}$$

The parameter, P, was then used to find the percentage of the large radius that is needed to find the value of the smaller radius (Equation C-10). Once the percentage was found, it was multiplied by the large radius to find the smaller radius (Equation C-11).

$$Percentage = (-0.0086 \times P) + 0.715 = (-0.0086 \times 22.82) + 0.715 = 0.519 \quad \text{(C-10)}$$

$$Small\ Radius\ (ft) = Percentage \times Large\ Radius = 0.519 \times 69305\ ft = 35969\ ft \quad \text{(C-11)}$$

The smaller circle was drawn with the calculated radius, centered on the center of the large circle. This process is displayed in Figure C.13. The red circle is the large circle, the red dot marks the center of the circle, and the blue circle represents the small circle.

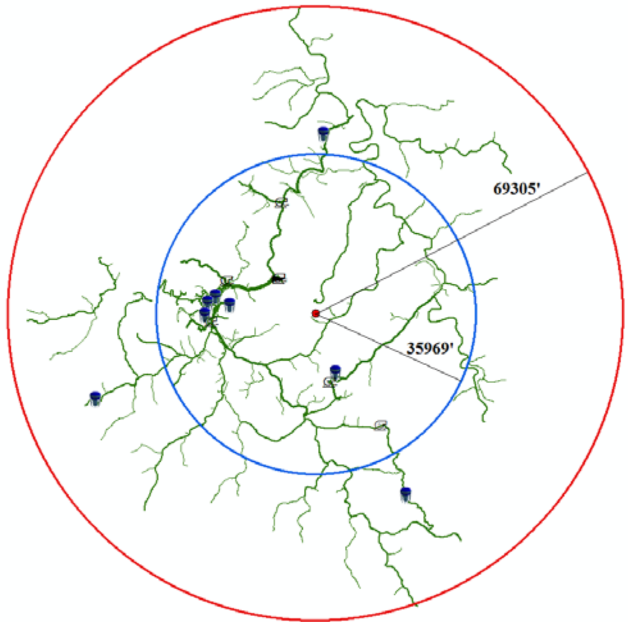


Figure C.13: Ideal Tank Selection Process (KY 15).

All storage tanks that were located outside of the small circle were eliminated as possibilities for the ideal tank. After this process, five tanks (out of the eight tanks present in the system) were considered possibilities for the ideal tank. The remainder of the tank selection process was executed by completing step B. The tanks that are possibilities for the ideal tank are highlighted in Figure C.14.

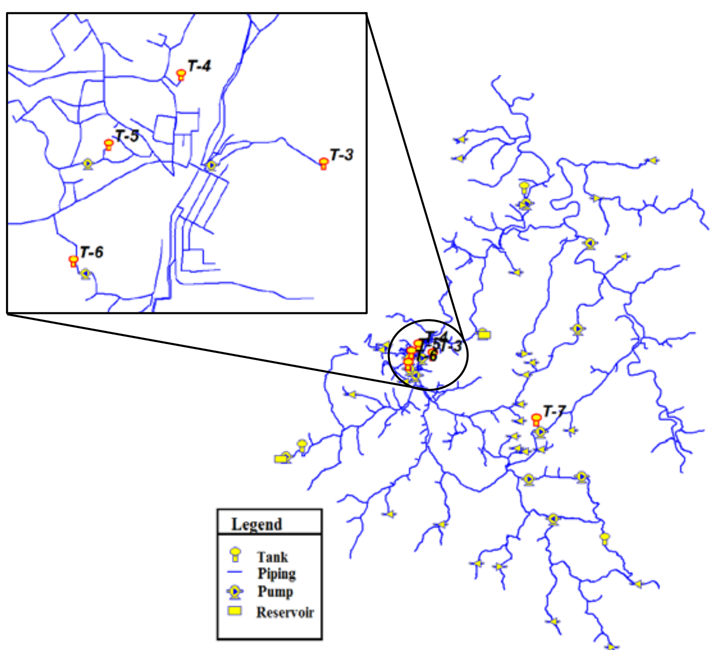


Figure C.14: Potential Ideal Tanks in KY 15.

B. The criteria for tank selection, along with the tanks that received points for each criterion, are outlined below. The data for the storage tanks, along with the total number of points awarded to each point is shown in Table C.7. This data only reflects the remaining tanks that were considered for the ideal tank after completing step A.

1) Lowest ground elevation: T-4
2) Lowest Hydraulic Grade Line (minimum water level in tanks): T-4
3) Lowest Hydraulic Grade Line (maximum water level in tanks): T-4
4) Located within a 2000 foot radius of a pump: T-5, T-6, and T-7
5) Located in a downtown area: T-3, T-4, T-5, and T-6 (see Figure C.14)

Table C.7: Tank Data and Point Totals (KY 15).

Tank	Elevation (ft)	HGL (Max level - ft)	HGL (Min level - ft)	Diameter (ft)	Volume (ft^3)	Within 2000' of Pump?	Located in Downtown Area?	Point Total
T-3	1027.2	1170	1135	56.2	86822	No	Yes	1
T-4	948.0	1085	1065	29.2	13393	No	Yes	4
T-5	1037.4	1180	1155	30.3	18027	Yes	Yes	2
T-6	1176.3	1215	1192	60.8	66777	Yes	Yes	2
T-7	1315.1	1370	1330	45.4	64753	Yes	No	1

T-4 received the highest number of points with four total, so T-4 was selected as the ideal tank in KY 15.

1a. Graphical Procedure. To find the optimal distance away from the ideal tank (identified in step 1) to place a sensor, specific information about the network was collected. First, the average length of water lines in the system (in feet) was required, found by dividing the total length of all pipelines in the system by the total number of pipes present. The area of the circle needed to encompass the entire system (drawn in step 1 during the tank selection process) was also needed. Because only the radius of the large circle was measured in the first step, Equation C-12 was first used to calculate the area of the circle.

$$A\,(mile^2) = \pi \times R^2 = \pi \times (13.17\ mi)^2 = 544.7\ mi^2 \qquad \text{(C-12)}$$

where A represents the area of the circle to encompass the entire system (mi^2) and R is the radius of this circle (mi). The branch parameter, B, was then calculated using Equation C-13.

$$B = \frac{Area\ of\ \ Circle\ to\ Cover\ System\ (mi^2)}{Average\ Pipe\ Length\ (mi)} = \frac{544.7\ mi^2}{2388.9\ \ ft \times \dfrac{1\ mile}{5280\ \ ft}} = 1203.9 \qquad \text{(C-13)}$$

The branch parameter, B, was then used in Equation C-14 in order to find the recommended distance from the tank.

$$Distance\,(ft) = 40.705 \times e^{(0.0015 \times 1203.9)} = 247.7\ \ ft \qquad \text{(C-14)}$$

247.7 feet is the recommended distance from the ideal tank that a water quality sensor should be placed, following the water lines. T-4 was selected as the ideal tank, and the node closest to this tank (J-476) is located 594.38 feet away from the tank. Because J-476 is the closest to the tank, and it is already slightly further away than the recommended distance, this node is the obvious choice for a sensor location using the graphical procedure. The selected node is labeled in Figure C.15, along with the length of the water lines near T-4.

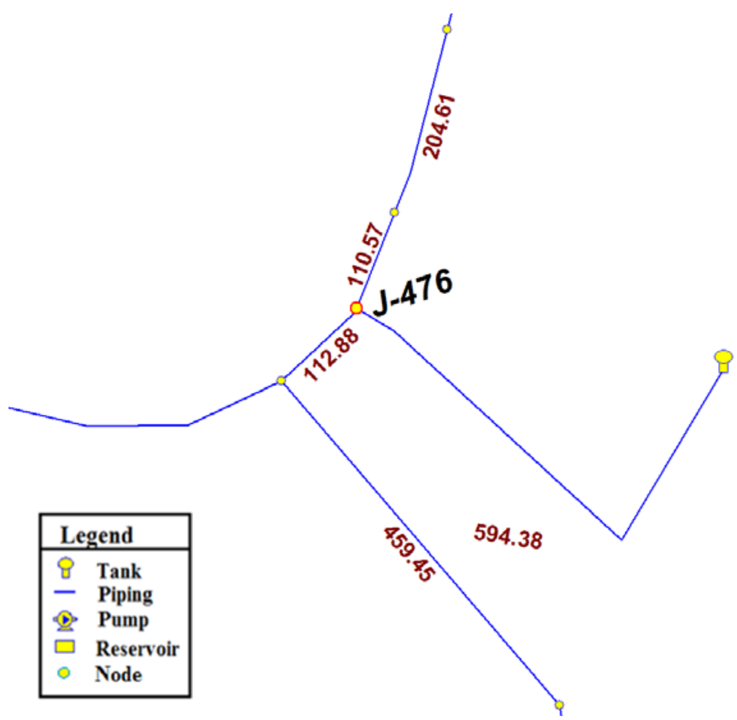


Figure C.15: Sensor Node Selection using the Graphical Procedure (KY 15).

2. Draw circle around selected tank. An equation was used to determine the necessary radius of the circle using the area of the large circle drawn to encompass the entire system. Equation C-15 was first used to calculate the area of the circle using the radius already measured. The variable R represents the radius of the large circle in miles.

$$A\,(mi^2) = \pi \times R^2 = \pi \times (13.13\,mi)^2 = 541.3\,mi^2 \qquad \text{(C-15)}$$

where A represents the area of the circle to encompass the entire system (mi^2) and R is the radius of this circle (mi). Next, the area of the circle was used in Equation C-16 to calculate the radius of the circle to be drawn around the ideal tank.

$$Radius\,(ft) = (7.9892 \times A) + 755.88 = (7.9892 \times 541.3\,mi^2) + 755.88 = 5080.4\ ft \qquad \text{(C-16)}$$

Because this tank was located in a downtown area, the radius needed to be multiplied by 0.2 (or divided by five). Therefore, the true radius to be used is shown in Equation C-17.

$$Radius\,(ft) = 0.2 \times 5080.4\ ft = 1016.1\ ft \qquad \text{(C-17)}$$

A circle with the calculated radius was drawn around the ideal tank. 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. This step is displayed in Figure C.16.

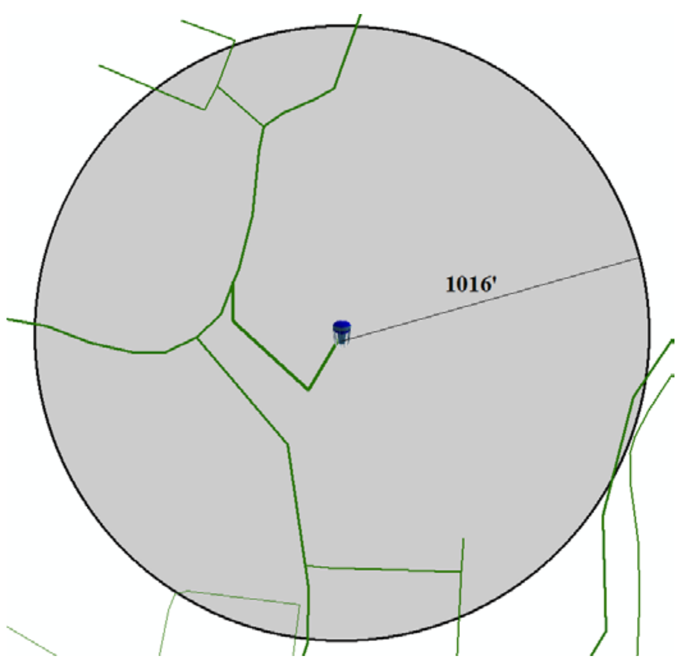


Figure C.16: Circle Around Ideal Tank (KY 15).

3. Define all nodes within the circle. This list of nodes within the circle was compiled, and these nodes were considered possible sensor locations. There were 11 nodes within the radius. However, five of these nodes would be considered "phantom nodes", meaning they were not located at the intersection of any pipes or a location where the pipe diameter or material changes. A typical utility manager who is simply using a map of their network to execute the procedure (instead of a model in KYPIPE) would not recognize these as nodes. Therefore, they would have to increase the radius by 500 foot increments until there were at least 10 nodes located within the circle. For this verification, the radius was left at 1016 feet since there were at least 10 nodes in the circle. The nodes located within the circle are shown in Figure C.17.

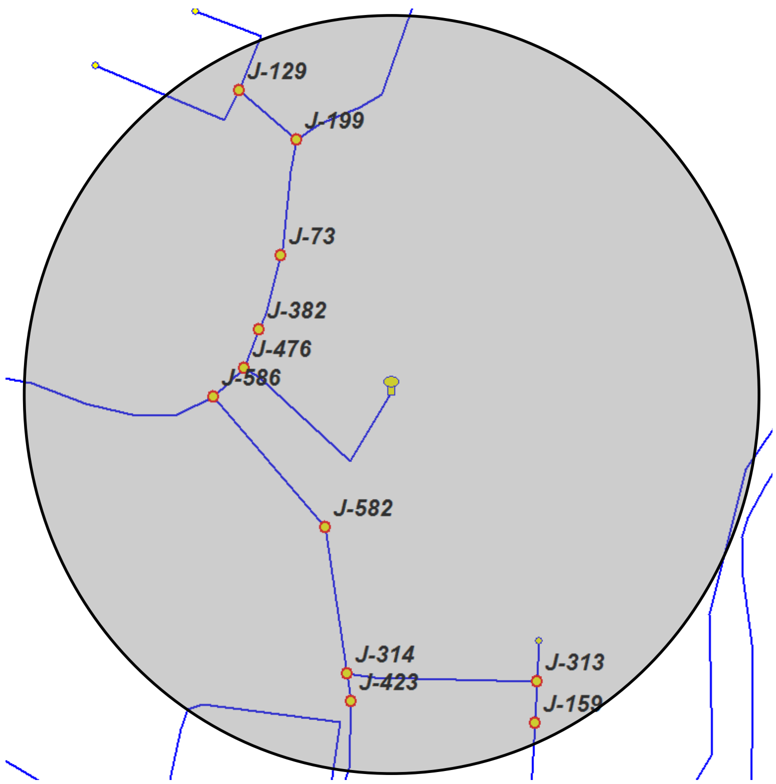


Figure C.17: Nodes Located within Circle Around Ideal Tank (KY 15).

4. Collect data for each node in the circle. The shortest distance from the node to the ideal tank following the water lines (in feet) and the number of pipes connected to the node (N_p) were recorded for each possible sensor location. For each node, the Distance/ N_p parameter was calculated. This data is displayed in Table C.8.

Table C.8: Data Collection of Nodes (KY 15).

Node	N_p	Distance (ft)	Distance / N_p
J-129	3	1421.72	473.91
J-159	2	2178.91	1089.46
J-199	3	1219.67	406.56
J-313	3	2068.36	689.45
J-314	3	1559.14	519.71
J-382	2	702.31	351.16
J-423	2	1634.38	817.19
J-476	3	591.74	197.25
J-582	2	1163.64	581.82
J-586	3	704.19	234.73
J-73	2	906.68	453.34

5. Rank the possible sensor locations. The set of possible sensor locations within the circle was ranked from the lowest value of Distance/ N_p to the highest value. The node ranked first (lowest value) is considered the optimal sensor location. For the KY 15 system, J-476 had the lowest value of Distance/ N_p and was therefore selected as the ideal sensor location.

Table C.9: Ranked Nodes (KY 15).

Node	N_p	Distance (ft)	Distance / N_p	Ranking
J-476	3	591.74	197.25	1
J-586	3	704.19	234.73	2
J-382	2	702.31	351.16	3
J-199	3	1219.67	406.56	4
J-73	2	906.68	453.34	5
J-129	3	1421.72	473.91	6
J-314	3	1559.14	519.71	7
J-582	2	1163.64	581.82	8
J-313	3	2068.36	689.45	9
J-423	2	1634.38	817.19	10
J-159	2	2178.91	1089.46	11

Appendix D

Development of Sensor Placement Guidance Procedure

This appendix contains data for the 12 main distribution system models (KY 1- KY 12) that were used to develop the sensor placement guidance procedure. Each section contains the relevant data used to develop each step of the guidance procedure, both the full (simplified) procedure and the graphical approach, for all three system configurations.

D.1 Development of Simplified Sensor Placement Procedure

Table D.1 displays a summary of the performance of the full simplified guidance procedure on KY 1 – KY 12. The table includes the total number of possible nodes for sensor locations, the selected node and average time to detection of the nodes selected by the KYPIPE sensor placement tool and the full guidance procedure, the ranking of the node selected by the guidance procedure (based on the times to detection provided by KYPIPE), and the difference in time to detection between the chosen nodes for the two methods.

Table D.1: Summary of Sensor Selection using Simplified Method (KY1 - KY12).

Config-uration	System	Possible Sensor Nodes	KYPIPE		Procedure			Time Difference (hr)
			Selected Node	Time to Detect (hr)	Selected Node	Time to Detect (hr)	Ranking	
Loop	KY 1	492	J-406	15.56	J-406	15.56	1	0
	KY 2	594	J-485	13.28	J-485	13.28	1	0
	KY 3	213	J-225	13.2	J-225	13.2	1	0
	KY 4	676	J-256	12.76	J-475	12.81	2	0.05
Grid	KY 5	285	J-13	9.39	J-321	9.42	2	0.03
	KY 6	379	J-114	11.04	J-114	11.04	1	0
	KY 7	375	J-271	15.29	J-14	15.46	3	0.17
	KY 8	916	J-541	17.27	J-632	17.32	3	0.05
Branch	KY 9	683	J-563	22.66	J-708	22.66	2	0
	KY 10	634	J-321	16.48	J-321	16.48	1	0
	KY 11	470	J-731	20.96	J-539	20.99	6	0.03
	KY 12	1827	J-1469	20.4	J-837	20.91	76	0.51

D.1.1 Development of Simplified Procedure (Loop Systems)

In order to select the ideal tank for the loop configured system, various criteria were used to assign points to tanks. The tank with the highest number of points was selected as the ideal tank. Various parameters relating to the tanks were found to be predictors of the ideal tank. Table D.2 displays data for all tanks in the loop systems, and Table D.3 shows the tank that was awarded points for each criterion used as a predictor, along with the tank selected as the ideal tank in each system.

Table D.2: Tank Information (Loop Systems).

System	Tank	Elevation (ft)	HGL (Max level - ft)	HGL (Min level -ft)	Diameter (ft)	Volume (ft^3)	Most Down-stream?	Located Interior?
KY 1	T-1	1344.8	1465	1430	99	269419	No	Yes
	T-2	1338.9	1450	1430	68	72634	No	Yes
	T-3	1348.3	1465	1440	60	70686	No	No
	T-4	1232.8	1425	1400	60	70686	Yes	Yes
KY 2	T-1	486.8	630	600	38	34023	Yes	Yes
	T-2	501	650	620	53	66186	No	Yes
	T-3	490.5	650	610	65	132732	No	No
KY 3	T-1	459.3	620	600	65	66366	No	No
	T-2	452.8	625	605	58	52842	No	No
	T-3	465.9	595	570	44	38013	Yes	Yes
KY 4	T-1	646.1	750	725	58	66052	Yes	Yes
	T-2	680.6	785	765	46	33238	No	Yes
	T-3	714.2	825	803	44	33452	No	Yes
	T-4	723.7	830	795	70	134696	No	No

Table D.3: Selection of Ideal Tank (Loop Systems).

System	Selection Criteria					Tank with Highest Number of Points
	Furthest Downstream of Source/WTP (located interior)	Lowest HGL (Min level)	Lowest HGL (Max level)	Lowest Elevation	Smallest (in volume)	
KY 1	T-4	T-4	T-4	T-4	T-3/T-4	T-4
KY 2	T-1	T-1	T-1	T-1	T-1	T-1
KY 3	T-3	T-3	T-3	T-2	T-3	T-3
KY 4	T-1	T-1	T-1	T-1	T-3	T-1

It is logical that the set of criteria used to select the ideal tank acted as indicators for the tank surrounded by the nodes with the fastest times to detection. Because the time to detect objective function was used in this study, the nodes with the fastest times should be located more downstream. If the sensor was located more upstream, all contaminants injected downstream of the sensor would not be detected, resulting in a very high value for the time to detection (the time to detect for contamination events not detected by the particular sensor location was set to 24 hours for calculation of the average time to detection by KYPIPE). Therefore, it is logical that one of the criteria specifies the tank be located furthest downstream of the source.

During the investigation of the nodes with the fastest times to detection in each of the 12 systems, it was found that these nodes tended to have lower average values of pressure than nodes with higher times to detection. Although data for flows and pressures were not directly used in development of the sensor placement procedure, this information was relevant in the ideal tank selection step. Tanks located at higher elevations with higher hydraulic grade lines tend to result in higher pressures in the surrounding areas. Because it was found that the most optimal sensor nodes typically had lower pressures, it is logical that the ideal tank should have lower hydraulic grade lines and be located at lower elevations than other tanks. This reasoning was also considering when selecting criteria for selection of the ideal tank in grid and branch systems, as many of the same criteria are also used for these systems.

After the ideal tank selection process, the required radius to draw the circle of influence around the ideal tank was computed. It was found that combining the total length of water lines in the system along with the approximate area the system covers resulted in a parameter that was a good predictor for the size of the radius necessary for each system. For each loop system (KY 1-KY 4), the ideal radius size was selected based on the number of nodes that were located within the circle. These ideal sizes resulted in the best relationship with the parameter R (found by dividing the total length of water lines in feet by the approximate area in square miles), and this relationship can be seen in Figure D.1. The data used to find this relationship is shown in Table D.4.

Table D.4: Radius around Ideal Tank (Loop Systems).

System	Total Length of Water Lines (ft)	Area of System (mi²)	R	Ideal Radius (ft)	Radius from Equation (ft)	Number of Nodes in Circle	Number of Nodes in Circle (Excluding Phantom Nodes)
KY 1	546968.5	11.8	46353.3	2000	1859.2	23	20
KY 2	499534.5	8.1	61670.9	1000	1102.6	17	17
KY 3	299486.8	5.5	54452.1	1500	1459.2	24	18
KY 4	855823.6	27.0	31697.2	2500	2583.3	19	19

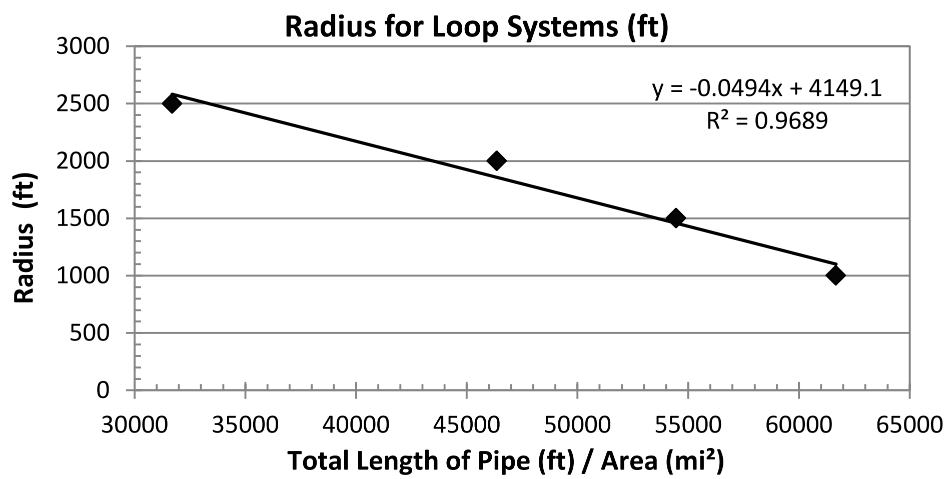


Figure D.1: Radius around Ideal Tank (Loop Systems).

The list of nodes located within the radius was then compiled, and the distance between the ideal tank and each node along with the number of pipes connected to each node (N_p) was recorded. The value of Distance/ N_p was calculated for each node, and the nodes were ranked in the order of increasing values of the parameter. The top ranked node is the node with the lowest value of the Distance/ N_p parameter. Table D.5 through Table D.8 show this data for KY 1 – KY 4, respectively. The values for N_p, distance between the tank and nodes following water lines, calculated Distance/ N_p parameter, rankings based on increasing values of Distance/ N_p, and the times to detection for each node (retrieved from the KYPIPE sensor placement tool) are shown for each system. Plots showing the time to detection (acquired from KYPIPE) vs. the value of Distance/ N_p for the potential sensor locations in each system are also displayed. These plots are intended to show the general trend of increasing time to detection with increasing values of Distance/ N_p. In each plot, the node that is displayed in red has the lowest value of Distance/ N_p.

Table D.5: Ranked Nodes and Time to Detection (KY 1).

Node	N_p	Distance (ft)	Distance / N_p	Ranking	Time to Detection (hr)
J-406	4	1332.35	333.1	1	15.56
J-235	3	1015.92	338.6	2	15.87
J-550	3	1211.12	403.7	3	16.46
J-234	2	917.57	458.8	4	16.44
J-407	3	1594.84	531.6	5	15.76
J-737	3	1651.12	550.4	6	15.57
J-744	3	1891.61	630.5	7	16.71
J-666	2	1277.43	638.7	8	16.45
J-389	3	1918.27	639.4	9	16.40
J-256	3	2013.31	671.1	10	15.95
J-385	3	2208.93	736.3	11	16.51
J-225	3	2278.42	759.5	12	16.21
J-275	3	2371.33	790.4	13	19.81
J-224	3	2486.38	828.8	14	16.77
J-743	2	1683.76	841.9	15	15.95
J-265	3	2844.3	948.1	16	16.80
J-770	2	1976.45	988.2	17	15.92
J-58	3	3020.59	1006.9	18	17.04
J-264	3	3694.58	1231.5	19	18.91
J-218	3	4060.15	1353.4	20	18.97
J-133	3	4204.55	1401.5	21	19.01
J-185	3	4225.49	1408.5	22	17.16
J-132	3	4499.63	1499.9	23	23.01

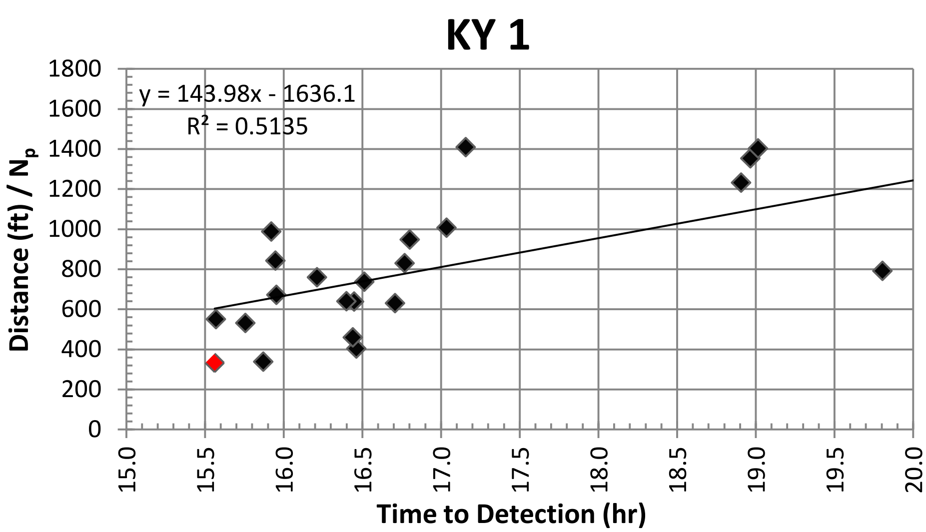


Figure D.2: Time to Detection vs. Distance / N_p (KY 1).

Table D.6: Ranked Nodes and Time to Detection (KY 2).

Node	N_p	Distance (ft)	Distance / N_p	Ranking	Time to Detection (hr)
J-485	3	180.01	60.00	1	13.28
J-138	3	320.01	106.67	2	13.30
J-356	3	343.59	114.53	3	13.57
J-357	3	363.33	121.11	4	13.79
J-355	3	373.57	124.52	5	13.95
J-139	4	875.7	218.93	6	13.46
J-241	3	663.78	221.26	7	14.00
J-240	3	695.5	231.83	8	14.26
J-218	4	927.51	231.88	9	13.63
J-70	4	1041.18	260.30	10	14.47
J-246	3	1067.98	355.99	11	14.55
J-219	4	1540.23	385.06	12	13.78
J-433	3	1173.93	391.31	13	13.89
J-154	3	1319.4	439.80	14	14.42
J-283	3	1868.43	622.81	15	14.30
J-245	3	1893.28	631.09	16	14.45
J-579	3	2251.07	750.36	17	15.03

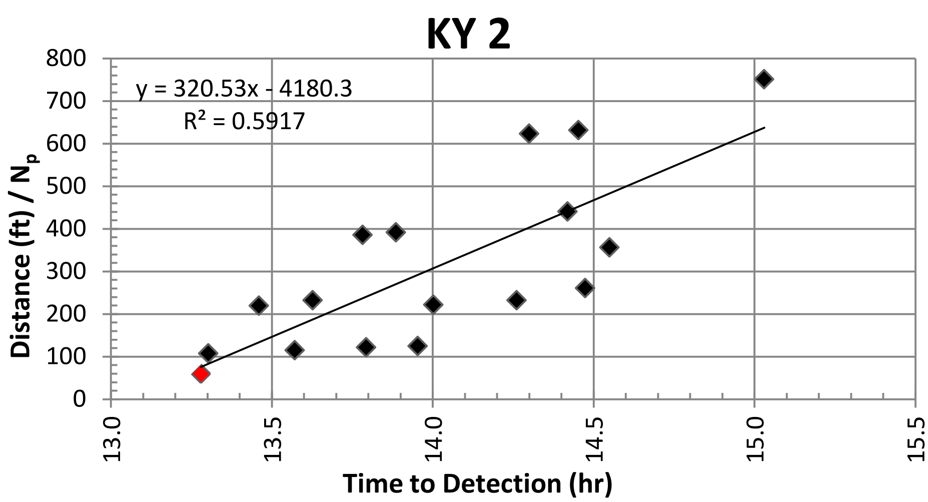


Figure D.3: Time to Detection vs. Distance / N_p (KY 2).

Table D.7: Ranked Nodes and Time to Detection (KY 3).

Node	N_p	Distance (ft)	Distance / N_p	Ranking	Time to Detection (hr)
J-225	3	107.95	35.98	1	13.20
J-204	3	282.12	94.04	2	13.53
J-180	3	822.07	274.02	3	14.10
J-18	3	865.8	288.60	4	14.10
J-140	4	1474.52	368.63	5	14.25
J-259	4	1629.05	407.26	6	14.59
J-120	4	1847.18	461.80	7	14.28
J-175	2	968.7	484.35	8	14.14
J-200	3	1686.8	562.27	9	14.05
J-176	3	1928.34	642.78	10	14.38
J-102	3	2136.72	712.24	11	15.06
J-201	3	2315.81	771.94	12	15.12
J-104	3	2403.88	801.29	13	14.78
J-168	3	2538.14	846.05	14	15.12
J-186	3	2623.26	874.42	15	14.27
J-127	2	1901.75	950.88	16	15.88
J-231	3	2870.71	956.90	17	15.96
J-107	2	2076.81	1038.41	18	15.16
J-117	3	3141.62	1047.21	19	16.25
J-210	3	3946.18	1315.39	20	15.84
J-118	2	2649.18	1324.59	21	15.70
J-268	2	2799.26	1399.63	22	16.15
J-103	2	2801.04	1400.52	23	16.76
J-236	2	4306.33	2153.17	24	17.36

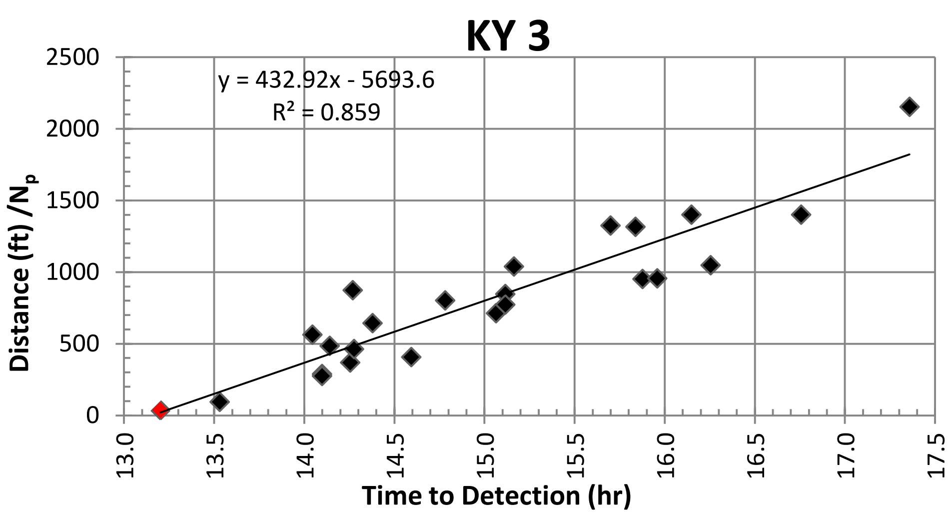


Figure D.4: Time to Detection vs. Distance / N_p (KY 3).

Table D.8: Ranked Nodes and Time to Detection (KY 4).

Node	N_p	Distance (ft)	Distance / N_p	Ranking	Time to Detection (hr)
J-475	3	609.58	203.19	1	12.81
J-256	4	1535.13	383.78	2	12.76
J-396	4	1569.17	392.29	3	14.48
J-488	4	2487.33	621.83	4	15.63
J-821	3	2073.9	691.30	5	14.93
J-408	4	2897.56	724.39	6	14.41
J-409	3	2174.1	724.70	7	12.98
J-87	4	2938.31	734.58	8	14.79
J-841	3	2575.33	858.44	9	16.32
J-251	3	3076.93	1025.64	10	14.80
J-249	3	3631.1	1210.37	11	16.06
J-252	3	3932.44	1310.81	12	17.65
J-572	3	4043.81	1347.94	13	14.60
J-296	3	4193.38	1397.79	14	14.77
J-289	3	4529.19	1509.73	15	15.08
J-773	3	4647.35	1549.12	16	14.88
J-774	3	5487.61	1829.20	17	15.50
J-749	3	6699.29	2233.10	18	16.30
J-775	3	7333.71	2444.57	19	24.00

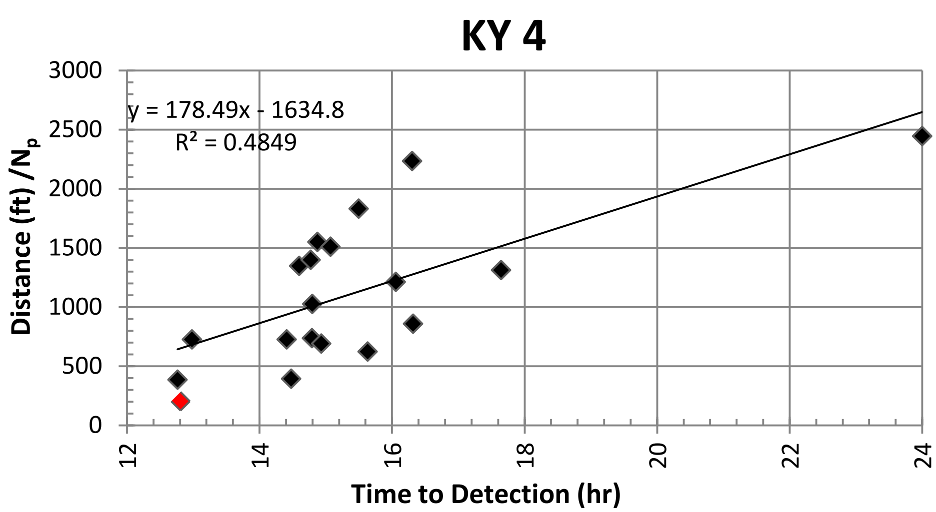


Figure D.5: Time to Detection vs. Distance / N_p (KY 4).

D.1.2 Development of Simplified Procedure (Grid Systems)

In order to choose the ideal tank for the grid configured system, a preliminary step was first executed if the system had at least five tanks. After this step eliminated a portion of the tanks as possibilities for the ideal tank (if applicable), various criteria were found to be indicators of the ideal tank. The tank that fit the most of the criterion was selected as the ideal tank. Table D.9 displays data for all tanks in the grid systems, and Table D.10 shows the tank that was awarded points for each criterion, along with the tank selected as the ideal tank in each system. It should be noted that information for all storage tanks in KY 9 is included, but only certain tanks were eligible for the ideal tank after the preliminary step was performed. The tanks that are still considered for the ideal tank are bold and italicized in Table D.9.

Table D.9: Tank Information (Grid Systems).

System	Tank	Elevation (ft)	HGL (Max level - ft)	HGL (Min level -ft)	Pressure Head (ft)	Diameter (ft)	Volume (ft³)	Most Down-stream ?	Located Interior ?
KY 5	T-1	887.4	970	945	25	53	55155	Yes	Yes
	T-2	901.4	960	925	35	68	127109	No	Yes
	T-3	898.1	960	925	35	68	127109	No	Yes
KY 6	T-1	762.5	905	880	25	58	66052	No	Yes
	T-2	740.2	905	885	20	65	66366	Yes	Yes
	T-3	825.7	925	890	35	31	26417	No	Yes
KY 7	T-1	532	690	650	40	65	132732	Yes	No
	T-2	566.1	693	676	17	78	81232	No	Yes
	T-3	622.9	740	715	25	58	66052	Yes	No
KY 8	***T-1***	992.3	1150	1125	25	58	66052	No	Yes
	T-2	1010.7	1160	1125	35	70	134696	No	No
	T-3	986.8	1135	1105	30	53	66186	No	Yes
	T-4	979	1135	1095	40	65	132732	Yes	No
	T-5	958.8	1110	1080	30	53	66186	No	Yes

Table D.10: Selection of Ideal Tank (Grid Systems).

System	Selection Criteria						Tank with Highest Number of Points
	Furthest Downstream of Source	Lowest HGL (Min level)	Lowest HGL (Max level)	Lowest Elevation	Smallest (in volume)	Lowest Head (max - min level)	
KY 5	T-1	T-2/T-3	T-2/T-3	T-1	T-1	T-1	T-1
KY 6	T-2	T-1/T-2	T-1	T-2	T-1	T-2	T-2
KY 7	T-1/T-3	T-1/T-2	T-1	T-1	T-3	T-2	T-1
KY 8	T-3	T-3	T-3	T-3	T-1	T-1	T-3

After the ideal tank selection process, the radius that is needed to draw the circle of influence around the ideal tank is computed. It was found that the same relationship used to predict the best value of the radius for the loop configured systems also worked well for the grid systems. This method combined the total length of water lines in the system along with the approximate area the system covered to calculate a parameter, R, which was a good predictor for the size of the radius necessary for each system. This relationship can be seen in Figure D.6. Although the equation is slightly different than that of the loop systems, the equations developed for the loop systems will be used for both loop and grid systems. It should be noted that the radius found from both the equation and the set of ranges for KY 7 was doubled because the ideal tank was located on the exterior of the system. Therefore, 5000 feet was used to develop the linear equation, but 2500 feet was the actual radius drawn around the ideal tank. The data used to find this relationship is shown in Table D.11.

Table D.11: Radius around Ideal Tank (Grid Systems).

System	Total Length of Water Lines in System (ft)	Area of System (mi^2)	R	Ideal Radius (ft)	Radius from Equation (ft)	Number of Nodes in Circle	Number of Nodes in Circle (Excluding Phantom Nodes)
KY 5	316865.4	6.1	51945.1	1500	1583.0	14	10
KY 6	403874.0	8.4	48080.2	2000	1773.9	24	11
KY 7	449636.8	11.9	37784.6	5000	4565.1	17	12
KY 8	811448.6	12.3	65971.4	1000	890.1	11	11

*The actual radius for KY 7 was 2500 ft (because the ideal tank was located exterior of the system). 5000 ft was used in trend development.

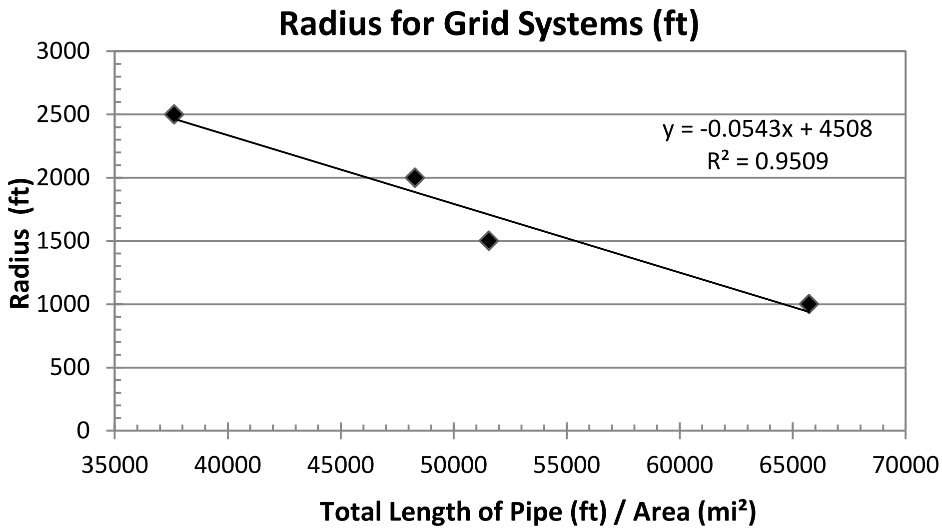


Figure D.6: Radius around Ideal Tank (Grid Systems).

Identical to the procedure for loop systems, the list of nodes located within the radius was compiled and the distance between the ideal tank and each node along with the number of pipes connected to each node (N_p) was recorded. The value of the Distance/ N_p parameter was calculated for each node, and the nodes were ranked in the order of increasing values of the parameter. Table D.12 through Table D.15 show this data for KY 5 – KY 8, respectively. The values for N_p, distance between the tank and nodes following water lines, Distance/ N_p, rankings based on increasing values of Distance/ N_p, and the times to detection for each node (generated by KYPIPE) are shown for each system. Plots showing the time to detection (acquired from KYPIPE) vs. the value of Distance/ N_p for each system are also displayed (Figure D.7 through Figure D.10). These plots are intended to show the general trend of increasing time to detection with increasing values of Distance/ N_p. In each plot, the node that is displayed in red has the lowest value of Distance/ N_p, and would therefore be selected as the ideal location using the procedure developed in this study.

Table D.12: Ranked Nodes and Time to Detection (KY 5).

Node	N_p	Distance (ft)	Distance / N_p	Ranking	Time to Detection (hr)
J-321	3	400.66	133.55	1	9.42
J-13	4	631.1	157.78	2	9.39
J-175	4	1012.65	253.16	3	10.02
J-338	3	806.49	268.83	4	9.89
J-58	3	1125.06	375.02	5	10.06
J-184	2	944.34	472.17	6	10.03
J-299	2	1077.54	538.77	7	9.48
J-60	3	1650.75	550.25	8	9.82
J-301	2	1101.8	550.90	9	10.30
J-253	3	1998.525	666.18	10	9.77
J-37	2	2345.04	1172.52	11	9.53
J-302	3	4629.24	1543.08	12	12.22
J-99	3	5013.2	1671.07	13	12.43
J-98	3	5358.1	1786.03	14	12.62

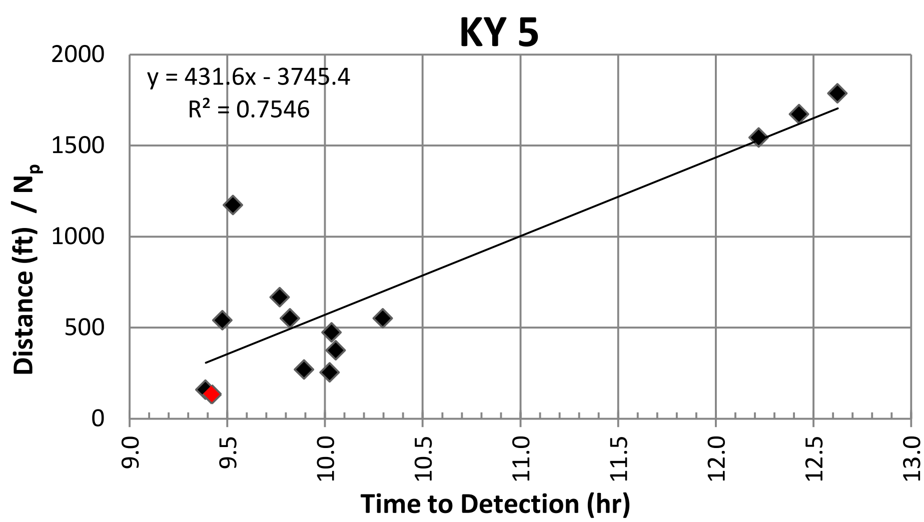


Figure D.7: Time to Detection vs. Distance / N_p (KY 5).

Table D.13: Ranked Nodes and Time to Detection (KY 6).

Node	N_p	Distance (ft)	Distance / N_p	Ranking	Time to Detection (hr)
J-114	3	326.17	108.72	1	11.04
J-80	4	1181.96	295.49	2	11.85
J-304	3	1439.05	479.68	3	12.62
J-381	3	1543.17	514.39	4	16.81
J-508	3	1836.01	612.00	5	12.69
J-250	3	1858.31	619.44	6	16.79
J-375	3	2151.1	717.03	7	16.80
J-79	2	1483.54	741.77	8	12.68
J-373	2	1519.97	759.99	9	16.81
J-78	2	1545.59	772.80	10	12.74
J-26	4	3300.45	825.11	11	13.59
J-113	2	1680.32	840.16	12	14.63
J-464	3	2561.91	853.97	13	13.22
J-327	2	1821.99	911.00	14	16.81
J-432	2	1959.2	979.60	15	12.91
J-328	2	2138.65	1069.33	16	16.80
J-315	3	3526.09	1175.36	17	13.65
J-62	3	4376.26	1458.75	18	15.83
J-465	2	3233.39	1616.70	19	13.61
J-413	2	3346.41	1673.21	20	13.71
J-87	2	3468.92	1734.46	21	13.67
J-88	2	3570.52	1785.26	22	13.62
J-89	2	3654.84	1827.42	23	13.65
J-118	2	3740.59	1870.30	24	13.65

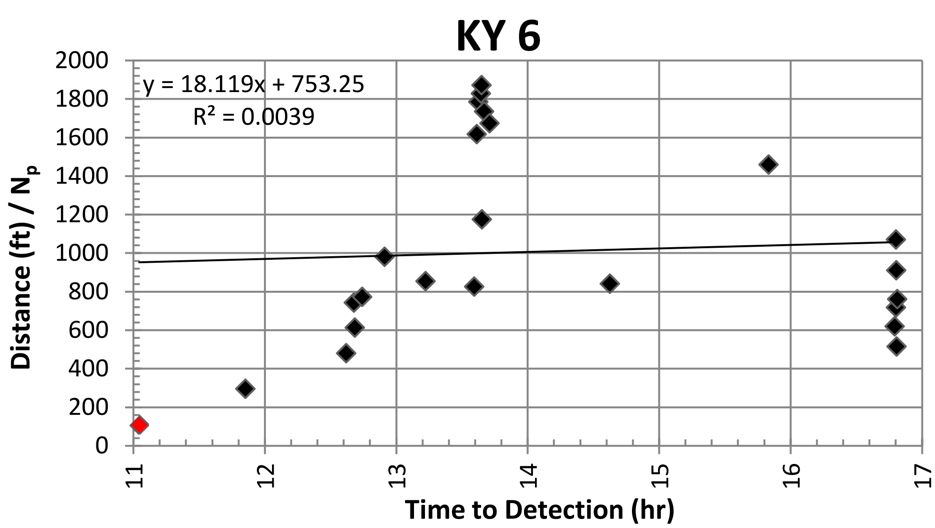


Figure D.8: Time to Detection vs. Distance / N_p (KY 6).

Table D.14: Ranked Nodes and Time to Detection (KY 7).

Node	N_p	Distance (ft)	Distance / N_p	Ranking	Time to Detection (hr)
J-14	3	1526.16	508.72	1	15.46
J-9	2	1148.78	574.39	2	15.43
J-13	3	2832.56	944.19	3	15.47
J-240	3	3891.07	1297.02	4	15.50
J-56	2	3126.69	1563.35	5	15.51
J-22	2	3508.51	1754.26	6	17.72
J-454	3	6040.83	2013.61	7	20.50
J-271	3	6750.69	2250.23	8	15.29
J-182	3	6832.68	2277.56	9	20.17
J-91	3	8104.94	2701.65	10	23.93
J-89	3	8204.01	2734.67	11	23.89
J-21	2	5963.52	2981.76	12	21.37
J-114	2	6922.39	3461.20	13	22.74
J-183	2	6923.89	3461.95	14	20.33
J-159	2	7661.71	3830.86	15	21.88
J-121	3	13272.87	4424.29	16	21.73
J-497	2	11185.62	5592.81	17	19.70

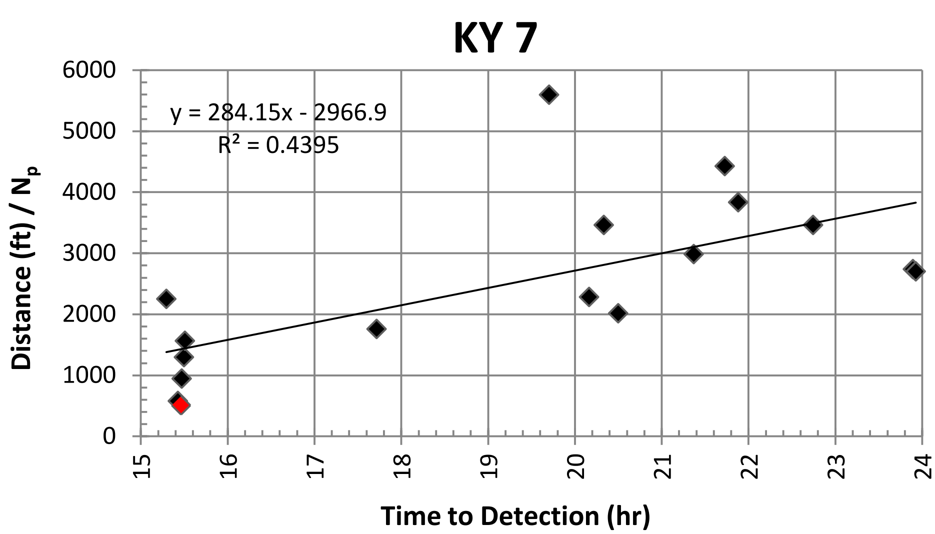


Figure D.9: Time to Detection vs. Distance / N_p (KY 7).

Table D.15: Ranked Nodes and Time to Detection (KY 8).

Node	N_p	Distance (ft)	Distance / N_p	Ranking	Time to Detection (hr)
J-632	3	125.19	41.73	1	17.32
J-541	4	343.71	85.93	2	17.27
J-540	3	483.95	161.32	3	17.32
J-582	2	438.52	219.26	4	17.56
J-144	4	1091.45	272.86	5	17.68
J-574	3	917.11	305.70	6	17.32
J-458	3	926.81	308.94	7	17.52
J-501	4	1300.23	325.06	8	17.80
J-616	3	995.47	331.82	9	17.60
J-756	3	1290.03	430.01	10	17.34
J-20	3	5996.6	1998.87	11	21.34

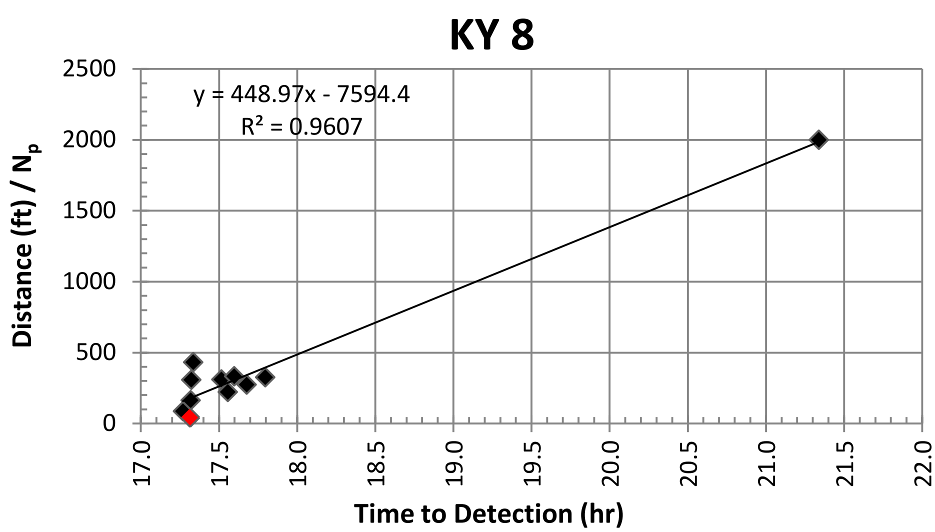


Figure D.10: Time to Detection vs. Distance / N_p (KY 8).

D.1.3 Development of Simplified Procedure (Branch Systems)

In order to choose the ideal tank for the branch configured system, several steps were necessary beyond what was executed for the loop and grid systems. A circle was drawn around the entire system, and then a smaller circle was also drawn centered at the center point of the larger circle. To find the percentage of the radius of the large circle needed to find the radius of the small circle, a parameter, P, was calculated (Equation D-1). The calculated parameter, P, was then used to find the percentage of the large radius that is needed to find the value of the smaller radius (Equation D-2). It was then multiplied by the large radius to find the smaller radius (Equation D-3).

$$P = \frac{Total\ Length\ of\ Water\ Lines\ in\ System\ (ft)}{Radius\ of\ Large\ Circle\ to\ Cover\ Entire\ System\ (ft)} \quad \text{(D-1)}$$

$$Percentage = (-0.0086 \times P) + 0.715 \quad \text{(D-2)}$$

$$Small\ Radius\ (ft) = Percentage \times Large\ Radius\ (ft) \quad \text{(D-3)}$$

The data used to develop this step is displayed in Table D.16 and Figure D.11. The KY 11 system contains 28 storage tanks. Because the procedure developed in this study is only able to provide sensor placement guidance for branch systems with 20 or less storage tanks, data for KY 11 was not included in the ideal tank selection step. Therefore, this step was developed only using data from KY 9, KY 10, and KY 12. Table D.17 displays the required system information, the parameter P, the percentage of the large radius required, and the value for the small radius in feet. Figure D.11 displays the plot showing the relationship between the parameter P and the required percentage of the large radius. The ideal percentage was established in each system by visual inspection and a satisfactory relationship was found between these values and the parameter P.

Table D.16: Data for Calculation of Small Radius (Branch Systems).

System	Total Length of Water Lines in System (ft)	Radius to Cover Entire System (ft)	P	Percentage	Small Radius (ft)
KY 9	3155866.4	81055	38.9	0.380	30813.9
KY 10	1410845.7	61914	22.8	0.519	32135.2
KY 12	2128105.1	66072	32.2	0.438	28939.8

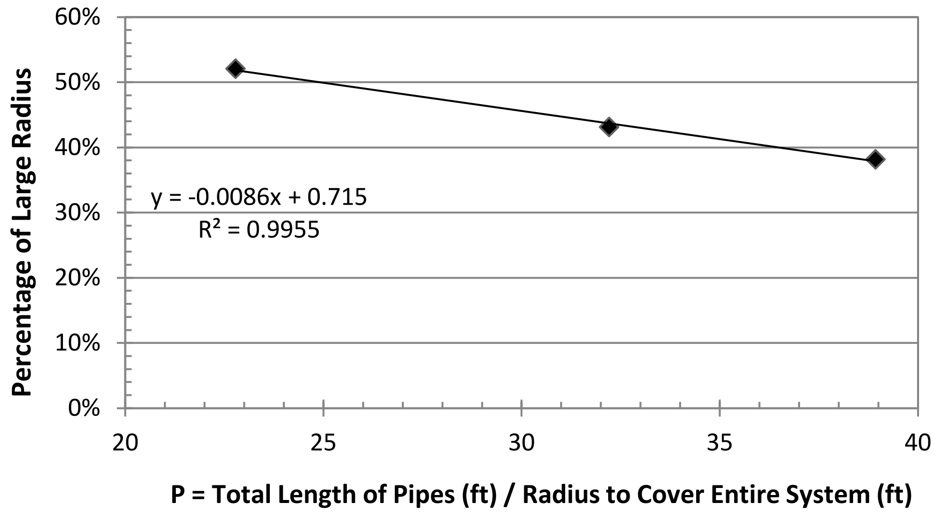


Figure D.11: Relationship between P and Percentage of Large Radius Required for Small Radius in Ideal Tank Selection (Branch Systems).

All tanks not located within the small circle were eliminated as possibilities for the ideal tank. The tank with the highest number of points, based on certain criteria that were found to be good indicators of the ideal tank, was selected as the ideal tank. Table D.17 displays data for all tanks in the branch systems, and Table D.18 shows the tank that was awarded points for each criterion, along with the tank selected as the ideal tank in each system. The data for KY 11 was excluded because this system contained too many tanks to be able to confidently predict the ideal tank. It should be noted that information for all storage tanks in the branch systems are included, but only certain tanks were eligible for the ideal tank after the first steps in the tank selection process was performed. The tanks that are still considered for the ideal tank are bold and italicized in Table D.17.

Table D.17: Tank Information (Branch Systems).

System	Tank	Elevation (ft)	HGL (Max level - ft)	HGL (Min level -ft)	Pressure Head (ft)	Diameter (ft)	Volume (ft³)	Located in Downtown Area?
KY 9	T-1	610.9	730	695	35	38	39694	No
	T-2	763.5	945	910	35	16	7037	No
	T-3	723.7	900	850	50	30	35343	No
	T-4	695.2	850	815	35	22	13305	No
	T-5	622.8	715	690	25	27	14314	No
	T-6	721.1	835	800	35	22	13305	No
	T-7	757.9	865	850	15	16	3016	No
	T-8	825.6	1045	1000	45	27	25765	No
	T-9	821.5	970	940	30	27	17177	No
	T-10	818.1	970	940	30	24	13572	No
	T-11	794.8	945	905	40	24	18096	No
	T-12	812.7	910	875	35	44	53219	No
	T-13	724.2	825	805	20	20	6283	No
	T-14	857.1	1015	975	40	30	28274	No
	T-15	919.7	1100	1065	35	27	20039	No
KY 10	T-1	839.2	985	965	20	30	14137	No
	T-2	717.3	815	790	25	40	31416	No
	T-3	942.2	1030	1004	26	20	8168	No
	T-4	975.4	1065	1050	15	30	10603	No
	T-5	735.6	875	860	15	58	39631	No
	T-6	742.3	875	840	35	50	68722	Yes
	T-7	757.7	905	875	30	52	63711	Yes
	T-8	823.2	965	930	35	52	74330	No
	T-9	811.4	965	945	20	40	25133	No
	T-10	865.8	1048	1025	22.5	36	22902	No
	T-11	923.4	1030	1005	25	26	13273	No
	T-12	951.6	1125	1100	25	26	13273	No
	T-13	959.5	1055	1025	30	25	14726	No
KY 12	***T-1***	992.3	1150	1125	25	58	66052	No
	T-2	1010.7	1160	1125	35	70	134696	No
	T-3	986.8	1135	1105	30	53	66186	No
	T-4	979.0	1135	1095	40	65	132732	No
	T-5	958.8	1110	1080	30	53	66186	No

Table D.18: Selection of Ideal Tanks (Branch Systems).

System	Selection Criteria					Tank with Highest Number of Points
	Lowest Elevation	Lowest HGL (Min water level)	Lowest HGL (Max water level)	Within 2000 ft of Pump	Located in Downtown Area	
KY 9	T-13	T-13	T-13	T-13	N/A	T-13
KY 10	T-6	T-6	T-6	T-8/T-9	T-6/T-7	T-6
KY 12	T-4	T-4	T-4	T-2/T-4	N/A	T-4

After the ideal tank selection process, the radius that is needed to draw the circle around the ideal tank is computed. The ideal radius for each system was estimated for each system (based on the number of nodes located within the given radius), and it was found that there was a strong relationship between the ideal radius and the area of the circle drawn to encompass the entire system (completed during the first part of the ideal tank selection step). This relationship can be seen in Figure D.12, and the data is displayed in Table D.9. Table D.9 also includes the number of nodes located within the circle around the ideal tank in each system, both including and excluding "phantom nodes." It should be noted that the radius for KY 10 was multiplied by 0.2 because the ideal tank was located in a downtown area. Therefore, the radius used in development of the linear trend was 4000 feet, but the actual radius drawn around the ideal tank was 750 feet. Although the KY 11 system contained too many tanks to use the guidance procedure to predict the ideal tank, data for this system will be included in the remaining steps.

Table D.19: Radius around Ideal Tank (Branch Systems).

System	Radius of Circle Encompassing Entire System (mi)	Area of Circle Encompassing Entire System (mi^2)	Estimate of Ideal Radius (ft)	Radius from Equation (ft)	Number of Nodes in Circle	Number of Nodes in Circle (excluding phantom nodes)
KY 9	81055	740.4	6500	6670.7	21	20
KY 10	61914	432.0	4000	4207.0	10	10
KY 11	92362	961.3	8500	8436.1	13	11
KY 12	66072	491.9	5000	4686.1	42	13

*Note: The actual radius for KY 10 was 750 ft (because the ideal tank was located in a downtown area). 4000 ft was used in trend development.

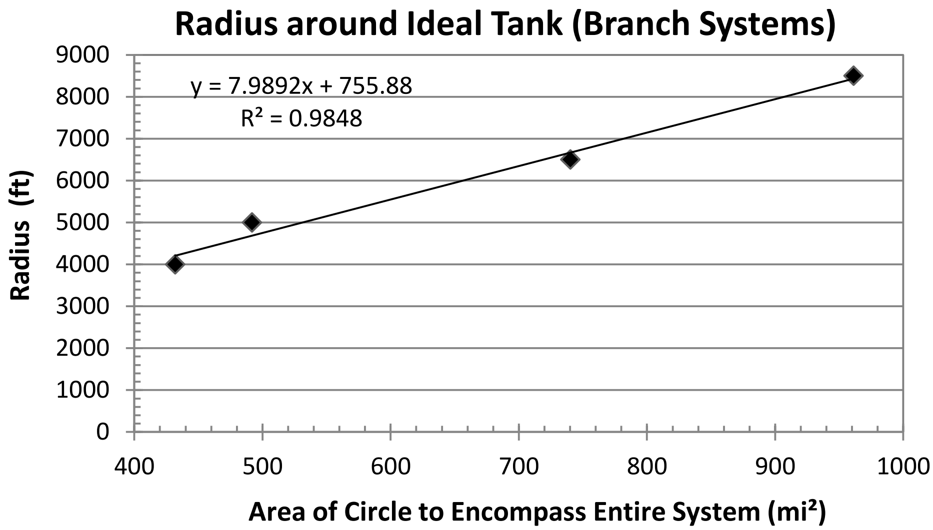


Figure D.12: Radius Around Ideal Tank (Branch Systems).

Identical to the procedure for loop and grid systems, the list of nodes located within the radius was compiled and the distance between the ideal tank and each node along with the number of pipes connected to each node (N_p) was recorded. The value of Distance/ N_p was calculated for each node, and the nodes were ranked in the order of increasing values of the parameter. Table D.20 through Table D.23 show this data for KY 9 – KY 12, respectively. The values for N_p, distance between the tank and nodes following the water lines, Distance/ N_p, the rankings based on increasing values of Distance/ N_p, and the times to detection for each potential sensor node (retrieved from the KYPIPE sensor placement tool) are shown for each system. Plots showing the time to detection (acquired from KYPIPE) vs. the value of Distance/ N_p for each system are also displayed. These plots are included to show the general trend of increasing time to detection with increasing values of Distance/ N_p. In each plot, the node that is displayed in red has the lowest value of Distance/ N_p, and would therefore be selected as the ideal location using the procedure developed in this study.

Table D.20: Ranked Nodes and Time to Detection (KY 9).

Node	N_p	Distance (ft)	Distance / N_p	Ranking	Time to Detection (hr)
J-708	3	226.48	75.5	1	22.66
J-40	3	2260.24	753.4	2	22.68
J-41	3	4407.69	1469.2	3	22.69
J-213	3	4822.94	1607.6	4	22.98
J-198	3	5138.03	1712.7	5	22.97
J-79	3	5385.68	1795.2	6	22.97
J-80	3	5605.31	1868.4	7	23.03
J-628	3	5857.65	1952.6	8	23.04
J-391	3	6297.56	2099.2	9	23.09
J-245	3	7009.13	2336.4	10	23.14
J-428	3	7825.15	2608.4	11	23.16
J-418	3	9042.25	3014.1	12	23.21
J-158	2	6324.32	3162.2	13	23.09
J-215	3	13837.34	4612.4	14	23.5
J-852	3	20395.95	6798.7	15	23.81
J-851	3	20924.17	6974.7	16	23.76
J-915	3	21256.78	7085.6	17	23.73
J-1041	3	22038.25	7346.1	18	23.77
J-1022	2	20109.39	10054.7	19	23.84
J-854	2	20654.37	10327.2	20	23.78

*Note: Pump-10 was removed from Data (Time to Detection=22.67 hr)

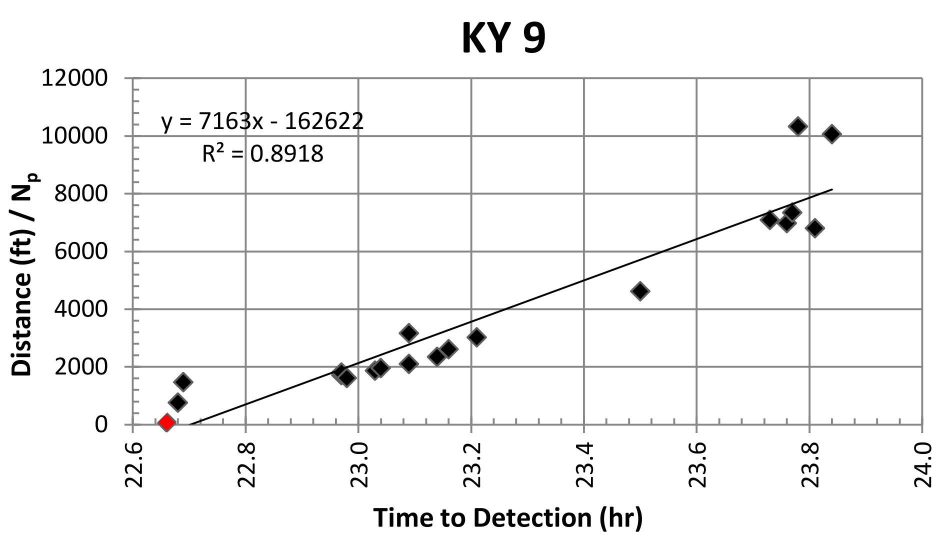


Figure D.13: Time to Detection vs. Distance / N_p (KY 9).

Table D.21: Ranked Nodes and Time to Detection (KY 10).

Node	N_p	Distance (ft)	Distance / N_p	Ranking	Time to Detection (hr)
J-321	3	381.27	127.09	1	16.48
J-550	3	669.99	223.33	2	16.73
J-652	3	899.32	299.77	3	17.63
J-539	3	902.79	300.93	4	16.74
J-423	3	944.44	314.81	5	16.91
J-322	2	644.71	322.36	6	16.68
J-330	3	1119.96	373.32	7	17.68
J-471	3	1322.9	440.97	8	17.77
J-92	4	1776.11	444.03	9	17.78
J-317	2	1460.75	730.38	10	17.85

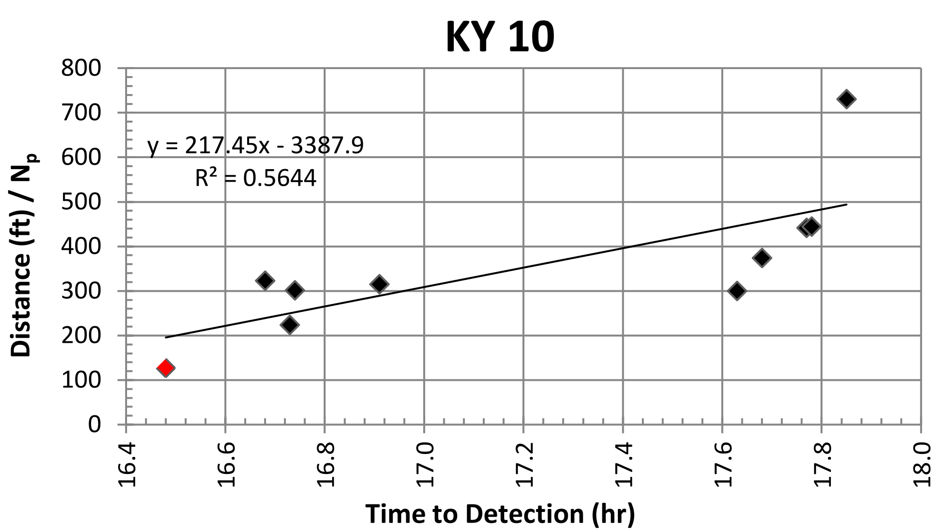


Figure D.14: Time to Detection vs. Distance / N_p (KY 10).

Table D.22: Ranked Nodes and Time to Detection (KY 11).

Node	N_p	Distance (ft)	Distance / N_p	Ranking	Time to Detection (hr)
J-539	3	1151.57	383.86	1	20.99
J-723	3	2246.27	748.76	2	20.97
J-657	3	2835.73	945.24	3	21.28
J-771	2	2082.67	1041.34	4	20.97
J-732	3	3727.49	1242.50	5	20.97
J-731	3	4800.9	1600.30	6	20.96
J-486	3	5020.18	1673.39	7	20.97
J-513	2	4510.87	2255.44	8	21.04
J-680	3	6795.32	2265.11	9	21.03
J-712	3	7455.54	2485.18	10	21.05
J-502	3	8316.28	2772.09	11	21.08
J-808	3	10137.67	3379.22	12	21.14
J-276	3	25221.52	8407.17	13	22.75

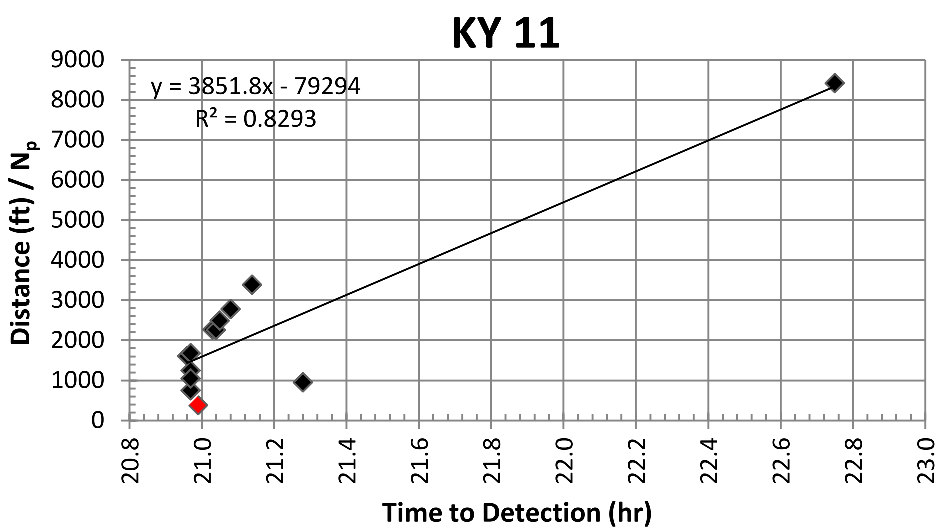


Figure D.15: Time to Detection vs. Distance / N_p (KY 11).

Table D.23: Ranked Nodes and Time to Detection (KY 12).

Node	N_p	Distance (ft)	Distance / N_p	Ranking	Time to Detection (hr)
J-837	3	1540.86	513.62	1	20.91
J-1802	2	1052.07	526.04	2	20.99
J-1760	3	2286.68	762.23	3	20.99
J-1460	3	2850.02	950.01	4	20.99
J-1109	3	3037.55	1012.52	5	20.93
J-610	3	3500.91	1166.97	6	20.41
J-2035	3	3642.04	1214.01	7	21.48
J-1110	3	4150.93	1383.64	8	20.92
J-1055	2	2928.8	1464.40	9	21.02
J-1166	3	4420.58	1473.53	10	20.44
J-1578	3	5325.71	1775.24	11	20.45
J-1625	2	4030.7	2015.35	12	20.99
J-1984	3	6059.99	2020.00	13	21.09
J-611	2	4367.29	2183.65	14	21.98
J-1415	2	4661.32	2330.66	15	21
J-1069	3	7530.22	2510.07	16	20.45
J-1861	2	5842.24	2921.12	17	21.95
J-883	2	5924.67	2962.34	18	20.49
J-882	2	6102.28	3051.14	19	20.47
J-2125	2	6262.7	3131.35	20	20.47
J-2393	2	6432.96	3216.48	21	21.1
J-2124	2	6459.28	3229.64	22	20.47
J-2372	2	6680.16	3340.08	23	20.47
J-195	2	6998.07	3499.04	24	20.46
J-2416	2	7062.63	3531.32	25	21.1
J-194	2	7285.72	3642.86	26	20.45
J-2369	2	7409.84	3704.92	27	21.11
J-1555	2	7779.65	3889.83	28	20.46
J-1556	2	8085.8	4042.90	29	20.49
J-729	3	12604.16	4201.39	30	20.92
J-223	3	12897.75	4299.25	31	21.23
J-2347	2	8901.89	4450.95	32	20.57
J-878	2	9473.84	4736.92	33	20.63
J-462	2	9766.84	4883.42	34	20.66
J-294	2	10473.26	5236.63	35	20.72
J-295	2	11456.63	5728.32	36	20.82
J-2318	2	12223.8	6111.90	37	20.89
J-235	2	12369.68	6184.84	38	21.16
J-2294	2	13013.08	6506.54	39	21.65

Node	N_p	Distance (ft)	Distance / N_p	Ranking	Time to Detection (hr)
J-2137	2	13169.16	6584.58	40	22
J-2138	2	13485.79	6742.90	41	22.87
J-2322	2	13611.41	6805.71	42	23.34

*Note: Pump-7 (Time to Detection=21.12 hr) and Pump-10 (Time to Detection = 20.42 hr) were removed from data. J-1909 (Time to Detection = 22.65 hr) and J-1829 (Time to Detection = 21.12 hr) were also removed from data because they were located within 500 feet of Pump-7.

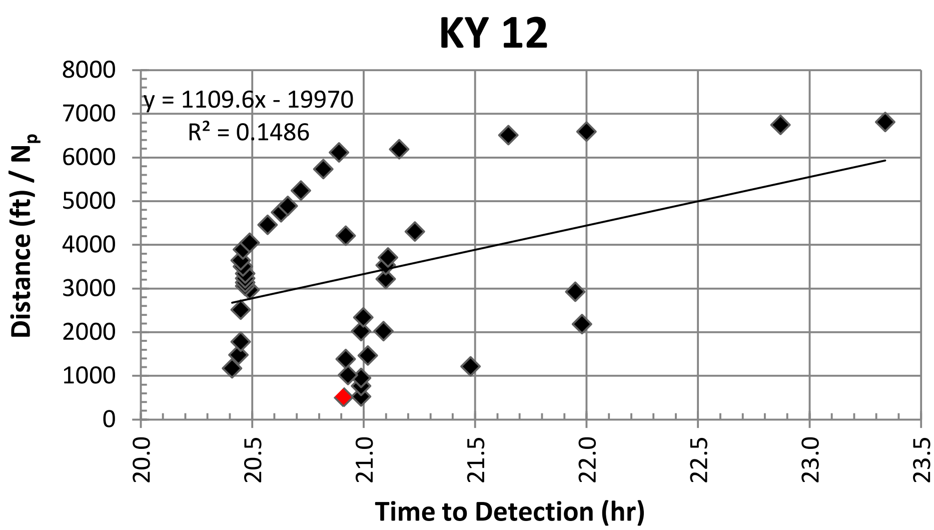


Figure D.16: Time to Detection vs. Distance / N_p (KY 12).

D.2 Development of Graphical Sensor Placement Procedure

The data in Table D.24 shows an evaluation of the performance of the shorter, graphical procedure on KY 1 – KY 12. The graphical procedure was meant to be faster and easier to execute. However, it was not intended to be as reliable in selecting the ideal location for sensor placement. Table D.24 displays the total number of possible nodes for sensor locations, the selected node, the time to detection from both the KYPIPE sensor placement tool and the graphical guidance procedure, the ranking of the node selected by the guidance procedure (based on the times to detection provided by KYPIPE), and the difference in time to detection between the selected nodes. In comparison between the full guidance procedure and the graphical method, the full procedure selected nodes with higher rankings (based on the times to detection produced by the KYPIPE tool) for five out of the 12 systems, and the graphical procedure selected better nodes for two of the 12 systems. The methods chose the same node for sensor placement in five of the 12 networks. This summary proves that although the graphical method produces similar results as the full procedure, the full procedure is slightly more reliable in selecting the ideal sensor node.

Table D.24: Summary of Sensor Selection using Graphical Method (KY 1- KY 12).

Config-uration	System	Possible Sensor Nodes	KYPIPE		Graphical Procedure			Time Differ-ence (hr)
			Selected Node	Time to Detect (hr)	Selected Node	Time to Detect (hr)	Ranking	
Loop	KY 1	492	J-406	15.56	J-235	15.87	5	0.31
	KY 2	594	J-485	13.28	J-138	13.3	2	0.02
	KY 3	213	J-225	13.2	J-204	13.53	2	0.33
	KY 4	676	J-256	12.76	J-475	12.81	2	0.05
Grid	KY 5	285	J-13	9.39	J-321	9.42	2	0.03
	KY 6	379	J-114	11.04	J-114	11.04	1	0
	KY 7	375	J-271	15.29	J-454	20.5	175	5.21
	KY 8	916	J-541	17.27	J-582	17.56	13	0.29
Branch	KY 9	683	J-563	22.66	J-708	22.66	2	0
	KY 10	634	J-321	16.48	J-321	16.48	1	0
	KY 11	470	J-731	20.96	J-732	20.97	4	0.01
	KY 12	1827	J-1469	20.4	J-610	20.41	2	0.01

Table D.25 also illustrates the performance of the graphical sensor placement procedure. The table displays the node with the fastest time to detection chosen by KYPIPE and the distance that this node is located from the ideal tank. The recommended distance from the ideal tank to the best sensor node (found using the developed exponential trend) along with the node selected using the graphical procedure and its distance from the ideal tank is also shown.

Table D.25: Graphical Procedure Results (KY 1 – KY 12).

Configuration	System	KYPIPE		Graphical Procedure		
		Selected Node	Distance from Ideal Tank (ft)	Predicted Distance from Ideal Tank (ft)	Selected Node	Distance from Ideal Tank (ft)
Loop	KY 1	J-406	1332.35	1084.76	J-235	1015.92
	KY 2	J-485	180.01	253.52	J-138	320.01
	KY 3	J-225	107.95	269.05	J-204	375.46
	KY 4	J-256	1535.13	950.83	J-475	609.58
Grid	KY 5	J-13	631.1	319.15	J-321	400.66
	KY 6	J-114	326.17	599.77	J-114	326.17
	KY 7	J-271	6750.69	5784.18	J-454	6040.83
	KY 8	J-541	343.71	432.63	J-582	438.52
Branch	KY 9	J-563	24337.99	423.01	J-708	226.48
	KY 10	J-321	381.27	499.54	J-321	381.27
	KY 11	J-731	4800.9	2867.58	J-732	3727.49
	KY 12	J-610	3500.91	3264.98	J-610	3500.91

*Note: In KY 12, J-1469 had fastest time to detection, but J-610 was the fastest node near the ideal tank. J-610 was used in order to develop trends for ideal distance from tank.

D.2.1 Development of Graphical Procedure (Loop Systems)

For the loop configured systems, a relationship was found using the total length of water lines present in the system divided by the number of tanks squared. Originally, only the KY 1 – KY 4 systems were used to develop this trend. However, it was noticed that these systems did not provide data for a large range of x values. In order to make this trend applicable to more systems, a new system was added. After examining all small utilities in KY that can be classified as loop systems, the system with the smallest value of the parameter (total length of water lines divided by the number of tanks squared) was selected. This system is referred to as KY 16. A hydraulic model was not created for this system, so the ideal distance between the tank and best sensor location was estimated based on experience with the remaining systems. Because this system was significantly smaller than the other systems, a conservative estimate of 100 feet was used. The addition of KY 16 allowed the trend to be applicable to a wider range of x values. Data for the five loop systems is shown in Table D.26, including the calculated parameter, the actual distance between the ideal tank and best sensor node, and the distance predicted by the regression equation. This data is also displayed in Figure D.17.

Table D.26: Data to Develop Graphical Procedure (Loop Systems).

System	Total Length of Pipes (ft)	Number of Tanks	Total Length of Pipes (ft) / # Tanks²	α x (Total Length of Pipes (ft) / # Tanks²)	Predicted Distance (ft)	Actual Distance (ft)
KY 1	499535	3	55503.8	55.50	1084.76	1332.35
KY 2	299487	3	33276.3	33.28	253.52	180.01
KY 3	546969	4	34185.5	34.19	269.05	107.95
KY 4	855824	4	53489.0	53.49	950.83	1535.13
KY 16	163352	4	10209.5	10.21	56.08	100.00

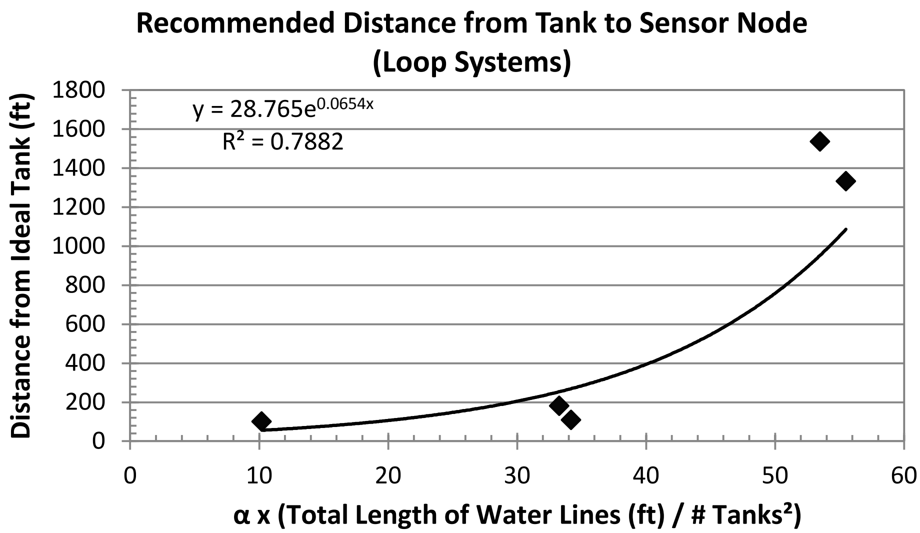


Figure D.17: Data to Develop Graphical Procedure (Loop Systems).

D.2.2 Development of Graphical Procedure (Grid Systems)

For the grid configured systems, a relationship was found using the total length of water lines present in the system divided by the number of pumps squared. Data for the grid systems is shown in Table D.27, including the calculated parameter, the actual distance between the ideal tank and best sensor node, and the distance predicted by the exponential equation. The plot showing this data along with the exponential trend line is shown in Figure D.18.

Table D.27: Data to Develop Graphical Procedure (Grid Systems).

System	Total Length of Pipes (ft)	Number of Pumps	Total Length of Pipes (ft) / # Pumps²	α x (Total Length of Pipes (ft) / # Pumps²)	Predicted Distance (ft)	Actual Distance (ft)
KY 5	316865	9	3911.9	3.91	319.15	631.1
KY 6	403874	2	100968.5	100.97	599.77	326.17
KY 7	449637	1	449636.8	449.64	5784.18	6750.69
KY 8	811449	4	50715.5	50.72	432.63	343.71

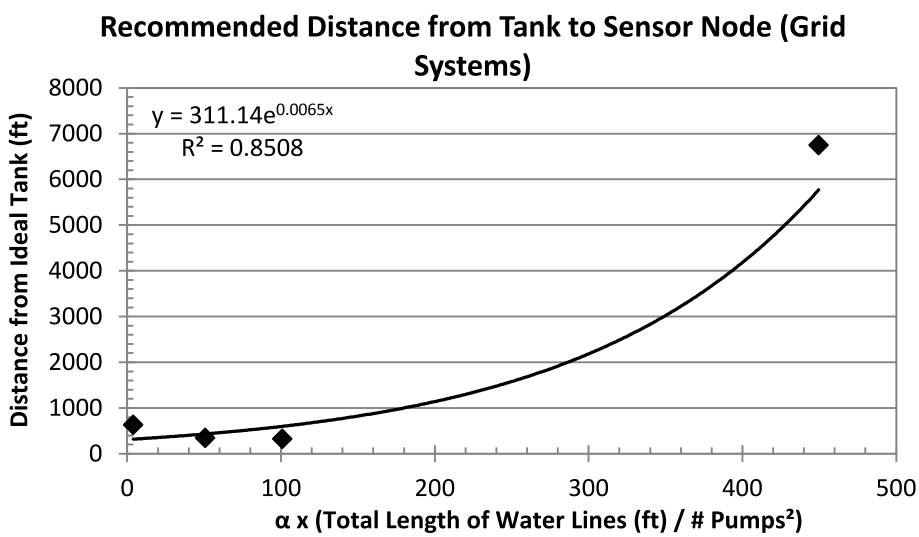


Figure D.18: Data to Develop Graphical Procedure (Grid Systems).

D.2.3 Development of Graphical Procedure (Branch Systems)

For the branch configured systems, a relationship was found using the area of the circle used to encompass the entire system (found in the tank selection process) divided by the average length of pipes in the system. The KY 9 – KY 12 systems were used to develop this trend. However, it was noticed that these systems did not provide data for a large range of x values. In order to make this trend applicable to more systems, a new system was added. After examining all small utilities in Kentucky that can be classified as branch systems, the system with the smallest value of the parameter (area of the circle to cover the entire system divided by the average pipe length) was selected. This system is referred to as KY 17. A hydraulic model was not created for this system, so the ideal distance between the tank and best sensor location was estimated based on experience with the remaining systems. Because this system was significantly smaller than the other systems, a conservative estimate of 100 feet was used. The addition of KY 17 allowed the exponential equation to be applicable to a wider range of x values.

It should also be noted that the node used to measure the optimal distance from the tank in KY 12 did not have the fastest time to detection in the entire system (it was ranked second). The node with the fastest time was not located near the ideal tank. Because the remainder of the fastest nodes in the system was located near a specific tank, this tank was still considered the ideal tank. The distance from the second fastest node was used as the data point for KY 12. The time to detection of the node actually ranked first in KY 12 is used when comparing the time to detection of the selected node using the developed procedure with the fastest time recorded for the system.

Data for the five branch systems is shown in Table D.28, including the calculated parameter, the actual distance between the ideal tank and best sensor node, and the distance predicted by the exponential equation (also shown in Figure D.19).

Table D.28: Data to Develop Graphical Procedure (Branch Systems).

System	Average Length of Pipes (ft)	Area of Circle to Cover System (mi^2)	Area of Circle (mi^2) / Average Pipe Length (mi)	Predicted Distance (ft)	Actual Distance (ft)
KY 9	2504.7	740.4	1560.7	423.01	226.48
KY 10	1364.5	432.0	1671.6	499.54	381.27
KY 11	1789.4	961.3	2836.6	2867.58	4800.9
KY 12	888.6	491.9	2923.1	3264.98	3500.91
KY 17	1505.78	81.9	287.2	62.62	100

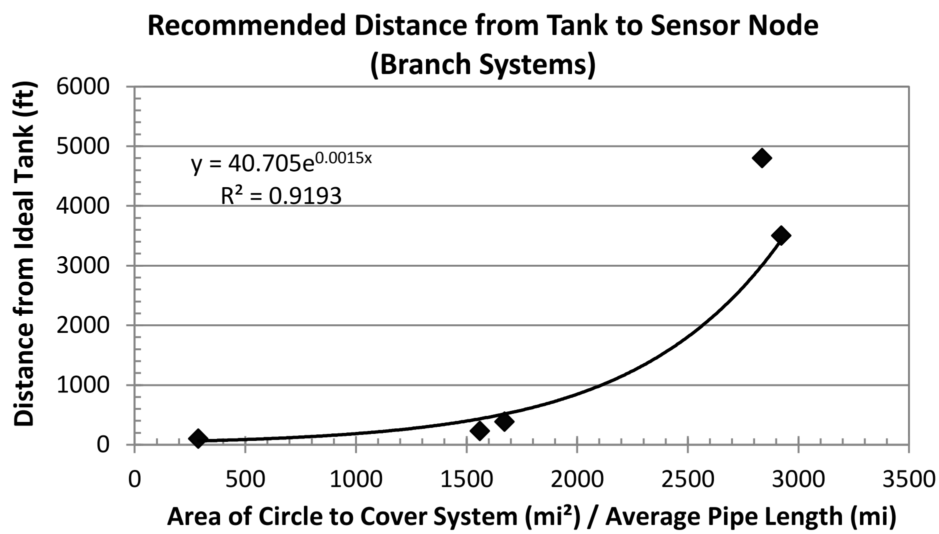


Figure D.19: Data to Develop Graphical Procedure (Branch Systems).

Appendix E

Results of Sensor Placement Simulations using KYPIPE and TEVA-SPOT

E.1 Results for Sensor Placement Simulations for Placement of One Sensor

Table E.1: Sensor Placement Results for TEVA-SPOT & KYPIPE (One Sensor)

System	Injection Rate (mg/min)	Injection Time (hours)	TEVA-SPOT		KYPIPE		
			Sensor Node	Time to Detection (min)	Sensor Node	Time to Detection (hr)	Time to Detection (min)
KY 1	4000	1	J-406	939.84	J-406	15.39	923.4
	2000	2	J-406	944.26	J-406	15.45	927.0
	1000	4	J-406	955.45	J-406	15.5	930.0
	500	8	J-406	971.31	J-737	15.83	949.8
	250	16	J-406	988.53	J-406	16.14	968.4
	1000	1	J-406	956.80	J-406	15.66	939.6
	1000	2	J-406	956.56	J-737	15.65	939.0
	1000	4	J-406	955.45	J-406	15.5	930.0
	1000	8	J-406	955.45	J-406	15.5	930.0
	1000	16	J-406	955.45	J-406	15.5	930.0
	600	4	J-406	968.61	J-406	15.74	944.4
	800	4	J-406	961.84	J-406	15.53	931.8
	1000	4	J-406	955.45	J-406	15.5	930.0
	1200	4	J-406	952.13	J-406	15.49	929.4
	1400	4	J-406	948.20	J-406	15.48	928.8
KY 2	4000	1	J-485	816.73	J-485	12.98	778.8
	2000	2	J-485	828.16	J-485	13.07	784.2
	1000	4	J-485	841.52	J-485	13.27	796.2
	500	8	J-139	862.26	J-485	13.74	824.4
	250	16	J-539	885.33	J-539	14.02	841.2
	1000	1	J-485	843.54	J-485	13.31	798.6
	1000	2	J-485	841.52	J-485	13.27	796.2
	1000	4	J-485	841.52	J-485	13.27	796.2
	1000	8	J-485	841.52	J-485	13.27	796.2
	1000	16	J-485	841.52	J-485	13.27	796.2
	600	4	J-139	859.63	J-139	13.63	817.8
	800	4	J-139	852.55	J-485	13.42	805.2
	1000	4	J-485	841.52	J-485	13.27	796.2
	1200	4	J-485	838.28	J-485	13.23	793.8
	1400	4	J-485	835.85	J-485	13.19	791.4
KY 3	4000	1	J-225	802.39	J-225	12.96	777.6
	2000	2	J-225	803.83	J-225	12.97	778.2
	1000	4	J-225	815.89	J-225	13.07	784.2
	500	8	J-225	827.66	J-225	13.27	796.2

System	Injection Rate (mg/min)	Injection Time (hours)	TEVA-SPOT		KYPIPE		
			Sensor Node	Time to Detection (min)	Sensor Node	Time to Detection (hr)	Time to Detection (min)
	250	16	J-225	842.87	J-225	13.48	808.8
	1000	1	J-225	815.89	J-225	13.09	785.4
	1000	2	J-225	815.89	J-225	13.08	784.8
	1000	4	J-225	815.89	J-225	13.07	784.2
	1000	8	J-225	815.89	J-225	13.07	784.2
	1000	16	J-225	815.89	J-225	13.07	784.2
	600	4	J-225	817.03	J-225	13.1	786.0
	800	4	J-225	816.17	J-225	13.09	785.4
	1000	4	J-225	815.89	J-225	13.07	784.2
	1200	4	J-225	815.02	J-225	12.99	779.4
	1400	4	J-225	810.14	J-225	12.98	778.8
KY 4	4000	1	J-256	773.70	J-256	12.54	752.4
	2000	2	J-256	779.29	J-256	12.63	757.8
	1000	4	J-256	787.41	J-256	12.75	765.0
	500	8	J-256	801.70	J-256	12.92	775.2
	250	16	J-256	843.48	J-256	13.64	818.4
	1000	1	J-256	792.68	J-256	12.85	771.0
	1000	2	J-256	787.59	J-256	12.78	766.8
	1000	4	J-256	787.41	J-256	12.75	765.0
	1000	8	J-256	786.34	J-256	12.73	763.8
	1000	16	J-256	786.34	J-256	12.73	763.8
	600	4	J-256	797.68	J-256	12.84	770.4
	800	4	J-256	791.79	J-256	12.78	766.8
	1000	4	J-256	787.41	J-256	12.75	765.0
	1200	4	J-256	785.45	J-256	12.73	763.8
	1400	4	J-256	783.75	J-256	12.7	762.0
KY 5	4000	1	J-13	593.94	J-13	9.26	555.6
	2000	2	J-321	592.20	J-13	9.27	556.2
	1000	4	J-13	595.45	J-13	9.29	557.4
	500	8	J-13	616.46	J-321	9.55	573.0
	250	16	J-299	636.82	J-321	9.78	586.8
	1000	1	J-321	612.13	J-13	9.38	562.8
	1000	2	J-13	599.57	J-13	9.3	558.0
	1000	4	J-13	595.45	J-13	9.29	557.4
	1000	8	J-13	594.37	J-13	9.29	557.4
	1000	16	J-13	593.29	J-13	9.29	557.4
	600	4	J-299	612.13	J-13	9.39	563.4

System	Injection Rate (mg/min)	Injection Time (hours)	TEVA-SPOT		KYPIPE		
			Sensor Node	Time to Detection (min)	Sensor Node	Time to Detection (hr)	Time to Detection (min)
	800	4	J-13	603.47	J-13	9.37	562.2
	1000	4	J-13	595.45	J-13	9.29	557.4
	1200	4	J-321	590.04	J-13	9.28	556.8
	1400	4	J-321	589.82	J-13	9.28	556.8
KY 6	4000	1	J-114	708.75	J-114	11.32	679.2
	2000	2	J-114	697.01	J-114	11.17	670.2
	1000	4	J-114	690.49	J-114	11.05	663.0
	500	8	J-114	694.24	J-114	11.04	662.4
	250	16	J-114	717.88	J-114	11.42	685.2
	1000	1	J-114	725.05	J-114	11.4	684.0
	1000	2	J-114	704.67	J-114	11.21	672.6
	1000	4	J-114	690.49	J-114	11.05	663.0
	1000	8	J-114	682.66	J-114	10.99	659.4
	1000	16	J-114	682.66	J-114	10.99	659.4
	600	4	J-114	699.29	J-114	11.09	665.4
	800	4	J-114	691.96	J-114	11.06	663.6
	1000	4	J-114	690.49	J-114	11.05	663.0
	1200	4	J-114	689.19	J-114	11.04	662.4
	1400	4	J-114	687.88	J-114	11.03	661.8
KY 7	4000	1	J-9	907.33	J-56	14.95	897.0
	2000	2	J-271	918.67	J-271	15.07	904.2
	1000	4	J-271	934.50	J-271	15.28	916.8
	500	8	J-271	949.00	J-271	15.47	928.2
	250	16	J-271	968.50	J-271	15.79	947.4
	1000	1	J-271	936.83	J-271	15.35	921.0
	1000	2	J-271	936.83	J-271	15.35	921.0
	1000	4	J-271	934.50	J-271	15.28	916.8
	1000	8	J-271	933.33	J-271	15.24	914.4
	1000	16	J-271	931.33	J-271	15.2	912.0
	600	4	J-271	946.50	J-271	15.41	924.6
	800	4	J-271	938.50	J-271	15.38	922.8
	1000	4	J-271	934.50	J-271	15.28	916.8
	1200	4	J-271	929.67	J-271	15.22	913.2
	1400	4	J-271	926.50	J-271	15.14	908.4
KY 8	4000	1	J-541	1114.58	J-541	17.64	1058.4
	2000	2	J-545	1089.89	J-541	17.18	1030.8
	1000	4	J-545	1082.85	J-541	17.23	1033.8

System	Injection Rate (mg/min)	Injection Time (hours)	TEVA-SPOT		KYPIPE		
			Sensor Node	Time to Detection (min)	Sensor Node	Time to Detection (hr)	Time to Detection (min)
	500	8	J-422	1088.89	J-949	17.21	1032.6
	250	16	J-422	1104.29	J-949	17.39	1043.4
	1000	1	J-541	1143.05	J-540	17.99	1079.4
	1000	2	J-756	1097.99	J-541	17.29	1037.4
	1000	4	J-545	1082.85	J-541	17.23	1033.8
	1000	8	J-455	1079.87	J-949	16.98	1018.8
	1000	16	J-455	1079.27	J-949	16.92	1015.2
	600	4	J-545	1088.23	J-756	17.36	1041.6
	800	4	J-545	1085.11	J-541	17.3	1038.0
	1000	4	J-545	1082.85	J-541	17.23	1033.8
	1200	4	J-565	1081.99	J-949	17.19	1031.4
	1400	4	J-565	1081.73	J-949	17.15	1029.0
KY 9	4000	1	J-814	1363.15	J-563	22.66	1359.6
	2000	2	J-814	1363.15	J-563	22.66	1359.6
	1000	4	J-708	1363.24	J-563	22.66	1359.6
	500	8	Pump-10	1362.69	J-563	22.66	1359.6
	250	16	J-708	1360.83	J-563	22.66	1359.6
	1000	1	J-708	1363.52	J-563	22.66	1359.6
	1000	2	J-708	1363.52	J-563	22.66	1359.6
	1000	4	J-708	1363.24	J-563	22.66	1359.6
	1000	8	J-708	1361.94	J-563	22.66	1359.6
	1000	16	J-708	1359.91	J-563	22.66	1359.6
	600	4	J-708	1363.33	J-563	22.66	1359.6
	800	4	J-814	1363.24	J-563	22.66	1359.6
	1000	4	J-708	1363.24	J-563	22.66	1359.6
	1200	4	J-708	1363.24	J-563	22.66	1359.6
	1400	4	J-708	1362.59	J-563	22.66	1359.6
KY 10	4000	1	J-321	992.15	J-321	16.49	989.4
	2000	2	J-321	993.21	J-321	16.5	990.0
	1000	4	J-321	995.02	J-321	16.48	988.8
	500	8	J-321	1000.38	J-321	16.52	991.2
	250	16	J-321	1040.57	J-321	16.58	994.8
	1000	1	J-321	995.02	J-321	16.49	989.4
	1000	2	J-321	995.02	J-321	16.49	989.4
	1000	4	J-321	995.02	J-321	16.48	988.8
	1000	8	J-321	995.02	J-321	16.47	988.2
	1000	16	J-321	995.02	J-321	16.47	988.2

System	Injection Rate (mg/min)	Injection Time (hours)	TEVA-SPOT		KYPIPE		
			Sensor Node	Time to Detection (min)	Sensor Node	Time to Detection (hr)	Time to Detection (min)
	600	4	J-321	999.33	J-321	16.49	989.4
	800	4	J-321	996.08	J-321	16.48	988.8
	1000	4	J-321	995.02	J-321	16.48	988.8
	1200	4	J-321	994.35	J-321	16.46	987.6
	1400	4	J-321	993.97	J-321	16.46	987.6
KY 11	4000	1	J-539	1264.25	J-539	20.95	1257.0
	2000	2	J-723	1263.56	J-731	20.93	1255.8
	1000	4	J-486	1264.52	J-731	20.96	1257.6
	500	8	J-539	1266.30	J-731	20.99	1259.4
	250	16	J-732	1270.27	J-731	21.01	1260.6
	1000	1	J-539	1264.93	J-539	20.99	1259.4
	1000	2	J-486	1264.52	J-731	20.96	1257.6
	1000	4	J-486	1264.52	J-731	20.96	1257.6
	1000	8	J-486	1264.52	J-731	20.96	1257.6
	1000	16	J-486	1264.52	J-731	20.96	1257.6
	600	4	J-723	1264.93	J-731	20.99	1259.4
	800	4	J-486	1264.79	J-731	20.96	1257.6
	1000	4	J-486	1264.52	J-731	20.96	1257.6
	1200	4	J-723	1263.97	J-731	20.96	1257.6
	1400	4	J-723	1263.56	J-731	20.96	1257.6
KY 12	4000	1	J-1069	1227.31	J-610	20.29	1217.4
	2000	2	J-1069	1230.05	J-610	20.34	1220.4
	1000	4	J-212	1236.31	J-1469	20.4	1224.0
	500	8	J-1469	1237.17	J-610	20.43	1225.8
	250	16	J-1469	1248.37	J-1469	20.61	1236.6
	1000	1	J-121	1281.58	J-695	21.01	1260.6
	1000	2	J-610	1239.01	J-610	20.46	1227.6
	1000	4	J-212	1236.31	J-1469	20.4	1224.0
	1000	8	J-1469	1230.81	J-610	20.35	1221.0
	1000	16	J-1469	1230.02	J-610	20.34	1220.4
	600	4	J-211	1243.99	J-1469	20.53	1231.8
	800	4	J-211	1240.10	J-1469	20.45	1227.0
	1000	4	J-212	1236.31	J-1469	20.4	1224.0
	1200	4	J-1255	1234.70	J-610	20.37	1222.2
	1400	4	J-1469	1232.62	J-610	20.35	1221.0

E.2 Results of Sensor Placement Simulations for Placement of Two Sensors

Table E.2: Sensor Placement Results for TEVA-SPOT & KYPIPE (Two Sensors)

System	Injection Rate (mg/min)	Injection Time (hours)	TEVA-SPOT			KYPIPE		
			Node #1	Node #2	Time to Detection (min)	Node #1	Node #2	Time to Detection (min)
KY 1	4000	1	J-235	J-497	817.25	J-235	J-497	798.6
	2000	2	J-235	J-497	822.17	J-235	J-497	802.8
	1000	4	J-235	J-497	834.47	J-235	J-497	807.0
	500	8	J-245	J-406	843.81	J-245	J-406	820.8
	250	16	J-244	J-406	852.30	J-244	J-406	826.8
	1000	1	J-245	J-406	838.65	J-235	J-497	817.8
	1000	2	J-245	J-406	838.40	J-235	J-497	809.4
	1000	4	J-235	J-497	834.47	J-235	J-497	807.0
	1000	8	J-235	J-497	834.47	J-235	J-497	807.0
	1000	16	J-235	J-497	834.47	J-235	J-497	807.0
	600	4	J-245	J-406	843.20	J-235	J-497	815.4
	800	4	J-244	J-406	839.39	J-235	J-497	808.8
	1000	4	J-235	J-497	834.47	J-235	J-497	807.0
	1200	4	J-235	J-497	825.74	J-235	J-497	805.8
	1400	4	J-235	J-497	824.14	J-235	J-497	804.6
KY 2	4000	1	J-138	J-533	446.71	J-485	J-533	408.6
	2000	2	J-485	J-533	452.68	J-485	J-533	406.8
	1000	4	J-138	J-533	446.31	J-485	J-533	396.0
	500	8	J-485	J-533	465.33	J-485	J-533	417.0
	250	16	J-485	J-534	491.74	J-139	J-533	440.4
	1000	1	J-138	J-533	467.56	J-485	J-533	418.8
	1000	2	J-485	J-533	466.04	J-485	J-533	415.2
	1000	4	J-138	J-533	446.31	J-485	J-533	396.0
	1000	8	J-138	J-533	443.07	J-485	J-533	396.0
	1000	16	J-138	J-533	441.75	J-485	J-533	394.8
	600	4	J-485	J-533	460.88	J-138	J-533	412.8
	800	4	J-138	J-533	452.07	J-485	J-533	403.2
	1000	4	J-138	J-533	446.31	J-485	J-533	396.0
	1200	4	J-138	J-533	444.49	J-485	J-533	394.8
	1400	4	J-138	J-533	443.37	J-485	J-533	393.6
KY 3	4000	1	J-2	J-225	577.90	J-2	J-225	546.6
	2000	2	J-2	J-225	571.87	J-2	J-225	538.2
	1000	4	J-2	J-225	575.02	J-2	J-225	531.6
	500	8	J-2	J-225	586.51	J-2	J-225	541.8
	250	16	J-2	J-225	606.32	J-2	J-225	555.0

System	Injection Rate (mg/min)	Injection Time (hours)	TEVA-SPOT			KYPIPE		
			Node #1	Node #2	Time to Detection (min)	Node #1	Node #2	Time to Detection (min)
	1000	1	J-2	J-225	595.41	J-2	J-225	553.2
	1000	2	J-2	J-225	587.66	J-2	J-225	544.8
	1000	4	J-2	J-225	575.02	J-2	J-225	531.6
	1000	8	J-2	J-225	573.59	J-2	J-225	531.6
	1000	16	J-2	J-225	573.59	J-2	J-225	531.6
	600	4	J-2	J-225	577.03	J-2	J-225	534.6
	800	4	J-2	J-225	575.89	J-2	J-225	533.4
	1000	4	J-2	J-225	575.02	J-2	J-225	531.6
	1200	4	J-2	J-225	574.16	J-2	J-225	528.0
	1400	4	J-2	J-225	569.00	J-2	J-225	527.4
	4000	1	J-475	J-610	718.93	J-475	J-610	703.8
	2000	2	J-475	J-610	722.41	J-475	J-610	705.6
	1000	4	J-475	J-610	730.27	J-475	J-610	711.0
	500	8	J-475	J-610	740.80	J-475	J-610	712.2
	250	16	J-475	J-610	757.86	J-256	J-641	735.6
	1000	1	J-475	J-641	735.54	J-475	J-641	714.6
	1000	2	J-475	J-610	730.36	J-475	J-641	712.8
KY 4	1000	4	J-475	J-610	730.27	J-475	J-610	711.0
	1000	8	J-475	J-610	728.66	J-475	J-610	708.6
	1000	16	J-475	J-610	728.66	J-475	J-610	708.6
	600	4	J-475	J-610	738.75	J-475	J-610	713.4
	800	4	J-475	J-610	733.13	J-475	J-610	711.6
	1000	4	J-475	J-610	730.27	J-475	J-610	711.0
	1200	4	J-475	J-610	729.11	J-475	J-610	709.2
	1400	4	J-475	J-610	726.79	J-475	J-610	708.6
	4000	1	J-247	J-321	520.29	J-247	J-299	484.8
	2000	2	J-247	J-321	516.82	J-247	J-299	486.6
	1000	4	J-13	J-247	520.51	J-13	J-247	487.8
	500	8	J-13	J-247	531.34	J-247	J-299	496.8
	250	16	J-321	J-334	544.98	J-159	J-321	505.2
	1000	1	J-247	J-321	528.95	J-247	J-299	493.2
KY 5	1000	2	J-13	J-247	526.79	J-13	J-247	490.2
	1000	4	J-13	J-247	520.51	J-13	J-247	487.8
	1000	8	J-247	J-321	518.12	J-13	J-247	487.8
	1000	16	J-247	J-321	518.12	J-13	J-247	487.8
	600	4	J-247	J-321	528.52	J-13	J-247	490.8
	800	4	J-247	J-321	524.40	J-247	J-299	489.0
	1000	4	J-13	J-247	520.51	J-13	J-247	487.8

System	Injection Rate (mg/min)	Injection Time (hours)	TEVA-SPOT			KYPIPE		
			Node #1	Node #2	Time to Detection (min)	Node #1	Node #2	Time to Detection (min)
	1200	4	J-247	J-321	515.09	J-247	J-299	486.0
	1400	4	J-247	J-321	514.87	J-247	J-299	486.0
KY 6	4000	1	J-114	J-476	620.71	J-114	J-365	593.4
	2000	2	J-114	J-130	608.64	J-114	J-130	583.8
	1000	4	J-114	J-130	600.65	J-114	J-130	574.8
	500	8	J-114	J-130	598.37	J-114	J-130	573.0
	250	16	J-114	J-130	619.40	J-114	J-130	588.0
	1000	1	J-114	J-476	636.20	J-114	J-365	595.2
	1000	2	J-114	J-476	615.82	J-114	J-130	585.0
	1000	4	J-114	J-130	600.65	J-114	J-130	574.8
	1000	8	J-114	J-130	592.83	J-114	J-130	571.8
	1000	16	J-114	J-130	592.83	J-114	J-130	571.2
	600	4	J-114	J-130	606.20	J-114	J-130	576.0
	800	4	J-114	J-130	602.61	J-114	J-130	575.4
	1000	4	J-114	J-130	600.65	J-114	J-130	574.8
	1200	4	J-114	J-130	600.33	J-114	J-130	579.6
	1400	4	J-114	J-130	599.35	J-114	J-130	579.6
KY 7	4000	1	J-15	J-9	709.00	J-13	J-15	690.0
	2000	2	J-15	J-9	712.17	J-13	J-15	691.2
	1000	4	J-15	J-9	715.00	J-13	J-15	697.2
	500	8	J-249	J-9	727.83	J-13	J-15	702.0
	250	16	J-249	J-9	737.33	J-13	J-15	714.0
	1000	1	J-15	J-9	716.50	J-15	J-9	699.0
	1000	2	J-15	J-9	715.67	J-15	J-9	699.0
	1000	4	J-15	J-9	715.00	J-13	J-15	697.2
	1000	8	J-15	J-9	714.83	J-13	J-15	696.6
	1000	16	J-15	J-9	714.83	J-13	J-15	696.6
	600	4	J-15	J-9	722.33	J-13	J-15	701.4
	800	4	J-15	J-9	718.00	J-13	J-15	698.4
	1000	4	J-15	J-9	715.00	J-13	J-15	697.2
	1200	4	J-15	J-9	714.83	J-13	J-15	696.6
	1400	4	J-15	J-9	713.67	J-13	J-15	692.4
KY 8	4000	1	J-540	J-576	925.75	J-541	J-890	886.8
	2000	2	J-545	J-576	926.95	J-574	J-576	876.6
	1000	4	J-296	J-451	920.84	J-1035	J-756	877.2
	500	8	J-422	J-451	925.89	J-451	J-756	884.4
	250	16	J-422	J-451	941.35	J-103	J-565	896.4
	1000	1	J-541	J-576	955.35	J-540	J-576	904.8

System	Injection Rate (mg/min)	Injection Time (hours)	TEVA-SPOT			KYPIPE		
			Node #1	Node #2	Time to Detection (min)	Node #1	Node #2	Time to Detection (min)
	1000	2	J-576	J-756	933.78	J-541	J-576	883.2
	1000	4	J-296	J-451	920.84	J-1035	J-756	877.2
	1000	8	J-296	J-451	916.66	J-1035	J-574	876.6
	1000	16	J-451	J-455	916.53	J-1035	J-574	874.2
	600	4	J-451	J-545	927.08	J-1035	J-756	882.6
	800	4	J-451	J-455	922.97	J-1035	J-756	879.0
	1000	4	J-296	J-451	920.84	J-1035	J-756	877.2
	1200	4	J-296	J-451	919.58	J-1035	J-574	874.2
	1400	4	J-103	J-296	918.92	J-1035	J-574	874.2
KY 9	4000	1	J-589	J-814	1302.13	J-563	J-589	1295.4
	2000	2	J-589	J-814	1301.67	J-563	J-589	1296.0
	1000	4	J-589	J-814	1302.13	J-563	J-589	1296.0
	500	8	J-589	Pump-10	1302.04	J-563	J-589	1296.0
	250	16	J-589	J-708	1300.46	J-563	J-589	1296.6
	1000	1	J-589	J-708	1302.87	J-563	J-589	1296.0
	1000	2	J-589	J-708	1302.41	J-563	J-589	1296.0
	1000	4	J-589	J-814	1302.13	J-563	J-589	1296.0
	1000	8	J-589	J-708	1300.83	J-563	J-589	1296.0
	1000	16	J-588	J-708	1298.70	J-563	J-589	1296.0
	600	4	J-589	J-708	1302.50	J-563	J-589	1296.0
	800	4	J-589	J-814	1302.13	J-563	J-589	1296.0
	1000	4	J-589	J-814	1302.13	J-563	J-589	1296.0
	1200	4	J-589	J-814	1301.94	J-563	J-589	1296.0
	1400	4	J-589	J-708	1301.30	J-563	J-589	1296.0
KY 10	4000	1	J-321	J-592	896.46	J-11	J-321	865.8
	2000	2	J-321	J-592	897.61	J-11	J-321	862.2
	1000	4	J-321	J-592	899.43	J-11	J-321	855.0
	500	8	J-321	J-592	903.64	J-11	J-321	857.4
	250	16	J-321	J-741	922.87	J-11	J-321	862.2
	1000	1	J-321	J-592	899.43	J-11	J-321	867.6
	1000	2	J-321	J-592	899.43	J-11	J-321	864.6
	1000	4	J-321	J-592	899.43	J-11	J-321	855.0
	1000	8	J-321	J-592	899.43	J-11	J-321	853.8
	1000	16	J-321	J-592	899.43	J-11	J-321	853.8
	600	4	J-321	J-592	902.49	J-11	J-321	857.4
	800	4	J-321	J-592	900.57	J-11	J-321	856.2
	1000	4	J-321	J-592	899.43	J-11	J-321	855.0

System	Injection Rate (mg/min)	Injection Time (hours)	TEVA-SPOT			KYPIPE		
			Node #1	Node #2	Time to Detection (min)	Node #1	Node #2	Time to Detection (min)
	1200	4	J-321	J-592	898.76	J-11	J-321	854.4
	1400	4	J-321	J-592	898.37	J-11	J-321	854.4
KY 11	4000	1	J-242	J-539	1188.90	J-242	J-539	1180.2
	2000	2	J-242	J-723	1188.22	J-242	J-731	1178.4
	1000	4	J-242	J-486	1189.18	J-242	J-731	1180.2
	500	8	J-242	J-539	1190.96	J-242	J-731	1182.6
	250	16	J-242	J-732	1195.07	J-242	J-731	1183.8
	1000	1	J-242	J-539	1189.59	J-242	J-539	1180.8
	1000	2	J-242	J-486	1189.18	J-242	J-731	1179.6
	1000	4	J-242	J-486	1189.18	J-242	J-731	1180.2
	1000	8	J-242	J-486	1189.18	J-242	J-731	1179.6
	1000	16	J-242	J-486	1189.18	J-242	J-731	1179.6
	600	4	J-242	J-723	1189.59	J-242	J-731	1179.6
	800	4	J-242	J-486	1189.45	J-242	J-731	1179.6
	1000	4	J-242	J-486	1189.18	J-242	J-731	1180.2
	1200	4	J-242	J-723	1188.63	J-242	J-731	1179.6
	1400	4	J-242	J-723	1188.22	J-242	J-731	1179.6
KY 12	4000	1	J-182	J-211	1178.91	J-182	J-211	1168.8
	2000	2	J-182	J-211	1180.86	J-182	J-211	1170.6
	1000	4	J-182	J-211	1184.84	J-1469	J-182	1171.2
	500	8	J-1469	J-182	1181.05	J-1469	J-182	1171.2
	250	16	J-1469	J-182	1183.82	J-1469	J-182	1171.8
	1000	1	J-183	J-211	1192.98	J-182	J-211	1179.0
	1000	2	J-182	J-211	1186.46	J-182	J-211	1175.4
	1000	4	J-182	J-211	1184.84	J-1469	J-182	1171.2
	1000	8	J-1469	J-182	1179.51	J-1596	J-48	1168.8
	1000	16	J-1469	J-182	1178.88	J-1596	J-48	1168.2
	600	4	J-183	J-211	1190.81	J-1469	J-182	1177.8
	800	4	J-182	J-211	1187.94	J-1469	J-182	1173.6
	1000	4	J-182	J-211	1184.84	J-1469	J-182	1171.2
	1200	4	J-1469	J-182	1183.72	J-1469	J-182	1171.2
	1400	4	J-1469	J-182	1182.17	J-1469	J-182	1170.6

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Vita

Stacey Schal was born and raised in Goshen, Kentucky. She graduated as the Valedictorian from North Oldham High School in 2008. Stacey attended the University of Kentucky and graduated Magna Cum Laude with a Bachelor's of Science in Civil Engineering in 2012. She obtained her Engineering in Training (EIT) Certificate in October of 2011 in the State of Kentucky. As an Undergraduate at UK, Stacey was active with Tau Beta Pi Engineering Honor Society, Alpha Phi Omega Service Fraternity, Chi Epsilon Civil Engineering Honor Society, and the American Society of Civil Engineers (served as the UK Chapter Treasurer). She also received the Outstanding Senior in Civil Engineering Award in 2012. Stacey was the recipient of the Presidential Scholarship and the Bechtel Award. During Graduate School at UK, Stacey remained involved with Tau Beta Pi, Chi Epsilon, and ASCE. She served as the Volunteer Coordinator for the Tau Beta Pi National Convention in 2012, and she was also the Vice President of the Chi Epsilon Chapter. Stacey is the first author on four publications:

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