Decision Support System for Evaluating Rural Water Supply Infrastructure Scenarios

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Introduction

Rural water systems often struggle to make decisions regarding their future, particularly when those decisions involve upgrading their infrastructure or consolidating / cooperating with other systems. This paper demonstrates the development of a step-by-step methodology that provides assistance to rural water systems for planning and updating their water supply infrastructure. The direct connection between the research methods and extension tools used are a unique component of the project, as contact and discussion with rural water system personnel was essential for project completion. The methodology is generalizable to any number of rural water systems, including those using either surface or groundwater. While we initially hoped the tools and methods used under this methodology would be able to be performed by non-specialists, such as local water district managers, our experience indicates that some specialist oversight is likely necessary. This system of evaluation should still dramatically enhance the capability of rural water districts to understand the limitations of their current system and give updates to the local community well in advance of any infrastructure crisis.

Background of Project

The 2007 Environmental Protection Agency (EPA) report of Drinking Water Infrastructure Needs Survey and Assessment stated that the United States would need an investment of about 335 billion dollars to upgrade its water infrastructure in the coming 20 years. The report said that out of this entire revenue, 60% would be required for just upgrading the distribution systems. The state-by-state classification of the report said that Oklahoma would need about 2.6 billion dollars, out of which 1.4 billion dollars would be required to upgrade the systems serving populations fewer than 3300 people (EPA, 2007). The Oklahoma Water

Resources Board (OWRB) set a new water plan to project water demands and the required inventory to meet these demands up to the year 2060. The preliminary goals of this project were as follows: (OWRB, 2009)

- Identify those regions having problems related to water supply
- Collect data, maps and other vital information regarding their water infrastructure
- Evaluate the performance of their systems on the basis of existing demands
- Identify the necessary changes in the system to meet future water demands.

OWRB identified 1717 active public water systems, out of which 1240 systems were community water systems, either municipal or rural water districts. Partners in this planning process were the Oklahoma Water Resources Research Institute, the Oklahoma Association of Regional Councils (COG's), Oklahoma Department of Environmental Quality (ODEQ) and federal partners. Based on the water plan for Oklahoma, a project goal was set to develop a cost efficient methodology, which would assist rural water districts in Oklahoma to manage and upgrade their drinking water distribution systems. Four rural water systems were chosen, representing systems with above ground storage, below ground storage, groundwater sources, and surface water sources. The four systems chosen were Beggs, Oklahoma, Braggs, Oklahoma, Kaw City, and Oilton, Oklahoma. These systems represented a variety of infrastructure issues, including insufficient storage, old pipes, and low pressure areas. In addition to the options in the systems selected, two different water distribution models were used during the project. The locations of the towns are shown in Figure 1 while the population, source of water, and general problems for these towns is given in Table 1.

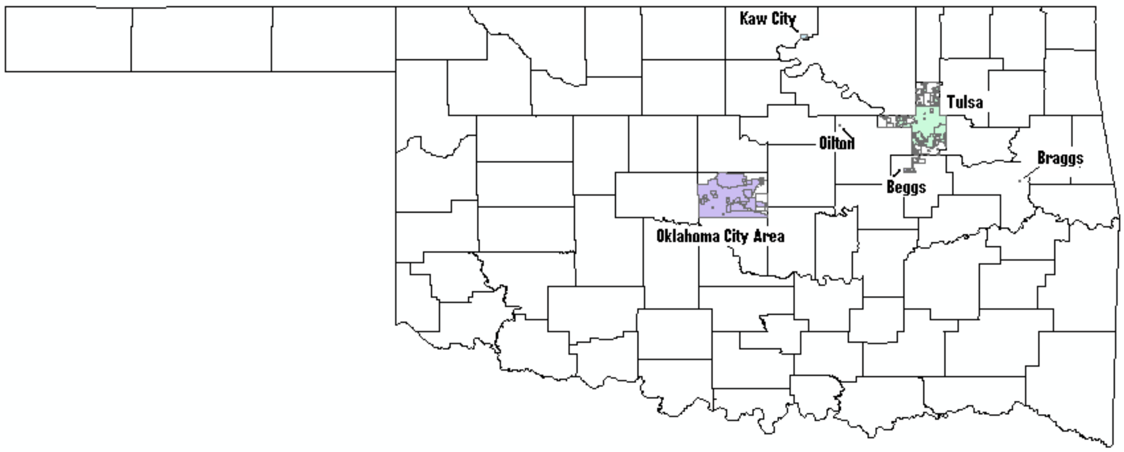

Figure 1. Location of Study Site Towns of Beggs, Braggs, Kaw City, and Oilton in Oklahoma

Table 1. Small Towns in Oklahoma Participating in Study of Water System Planning.

Item	Beggs	Braggs	Kaw City	Oilton
Population	1,364	1,030	400	1,200
Water Source	S.W.	G.W.	G.W.	G.W.
Gallons/Day (thos)	161	75.6	80	118
Treatment	Conventional.	NR	NR	NR
Storage (thos. gal.)	175[b]	200	200	950
Issues: Old pipes	yes	Yes	Yes	
Insufficient storage	Yes	No	Yes[c]	No
Low Pressure Areas	yes	yes	No	yes
Sufficient Fire Flow	No	Yes	Yes	No
Primary Standards	ok	ok	ok	ok
Secondary Standards	ok	ok	Mn	ok
Water Age	Some[d]	Some[d]	Some[d]	Some[d]

[a] Abbreviations used; S.W. = surface water, G.W. = ground water, NR = not required.
[b] 50,000 elevated plus 125,000 in ground tank.
[c] During summer tourist weekends.
[d] Generally in areas served by long un-looped pipes

The Kaw City System study involves potential regionalization of water treatment systems and has not been completed. Only one of the four towns had digital pipeline data set. In some cases, the hand drawn pipeline maps were incomplete. The approach in this study was to develop a hydrological simulation model for the town and then use that model to address the problems shown above in Table 1. The following approach was followed.

1) Contact and meet with appropriate local officials such as the mayor, manager, and/or city engineer.
2) Obtain copies of pipe line maps noting length, diameter, age, material, and condition, if possible. Alternatively sketch pipeline maps onto Google or Tiger line drawings of the city. Handheld GPS units were used to verify the location of critical infrastructure such as wells, treatment plants, and water storage units.
3) Obtain available technical information about the pumps, (size, power, model, age, power consumption, and hours of operation) and other system components.
4) Develop and validate an EPANET or WaterCAD simulation model for the water system.
5) Use the EPANET or WaterCAD models to evaluate the ability of the system to meet time of day demands by spatial location. The EPANET hydrological simulation program was developed by EPA and is available at no cost. WaterCAD is a commercial system distributed by Bentley Systems.
6) Determine the ability of the water distribution system to meet fire flow demands at each hydrant (minimum 20 psi after two hours of 250 gpm flow).
7) Evaluate the type, amount, and time of infrastructure needs to meet projected population growth.

Simulation Model Development

The Oklahoma Water Resources Board (OWRB) has developed a set of GIS pipeline drawings for some 800 rural water systems in Oklahoma; however, these drawings typically do not include small towns such as the ones included in this project. The first step was to develop the geographical information system (GIS) drawings of the major pipelines serving the city. Zonum Systems (2009) has developed several freeware interfaces to EPANET. One program, (EPANETZ) allows the user to digitize pipelines onto a Google Map of the town. Comparison of the Google map of the town with engineering drawings permits development of a digital infrastructure map with approximate (though not exact) location of pipelines. The program automatically creates the necessary linkages between nodes. The user must enter the pipe diameters and the node elevations. The GIS will provide estimates of the length of pipes, but actual lengths should be used when these are available. Two or more pipes are considered joined if they share the same node. One problem in getting EPANET to operate, is that slight differences in placement of pipe lines may generate multiple nodes which appear as a single node on one location. More expensive simulation programs link such nodes automatically. Excel macros were written to check the differences in latitude and longitude between nodes and ask the user if pipes having separate ending nodes within a specified radius should be connected, essentially requiring user verification for each unconnected node.

A second problem encountered was how to determine the elevation of each node, which is a required input for determining water flow. This is difficult for inexperienced users to accomplish in ARCVIEW or ARCMAP. However, a second relatively inexpensive GIS program, Global Mapper, was available that creates XYZ files (which include elevation) by simply overlaying the line drawing of the pipes on a USGS elevation file. Visual Basic macros were then used to add the elevations to the pipeline nodes. (Zonum Solutions (2009) now offers an online program to add elevations to nodes). The values relating to the depth of wells, height and volume of storage facilities, pump curves, rules for pump operation, and diurnal water use patterns must be added to the data set. The effect of corrosion in reducing pipe flows was also approximated after discussions with the city engineer.

The following three sections discuss the steps taken to evaluation the distribution systems in Beggs, Oilton, and Braggs, respectively. As indicated, free EPANET software was used in both Beggs and Braggs, while Oilton incorporated the for-fee WaterCAD software typically used by professional engineers. A discussion of the issues faced during each simulation is included. Additionally, the analysis of Beggs (which was completed prior to Oilton and Braggs) incorporates a methodology for assessing the cost of potential upgrades to the existing infrastructure.

Simulation Model to Evaluate the Beggs Water Distribution System

The EPANET model developed for the City of Beggs will be used to illustrate the capabilities of the water simulation software to analyze problems and possible solutions for a small town (Lea, 2009).

Figure 2 shows the digitized pipeline for the City of Beggs overlaid on photo map of the city. The low pressure areas indicated by circles along with the areas where the age of water in the pipes was problematic on Figure 2 were confirmed by the city engineer. One area with pressure problems and inadequate fire flow was on the west end where the primary and secondary schools were located. A similar problem was encountered with the “Hilltop” area on the east. Both of these areas represent city expansions made after the initial water system was developed. The dead ends associated with several long pipes also failed the fire-flow test.

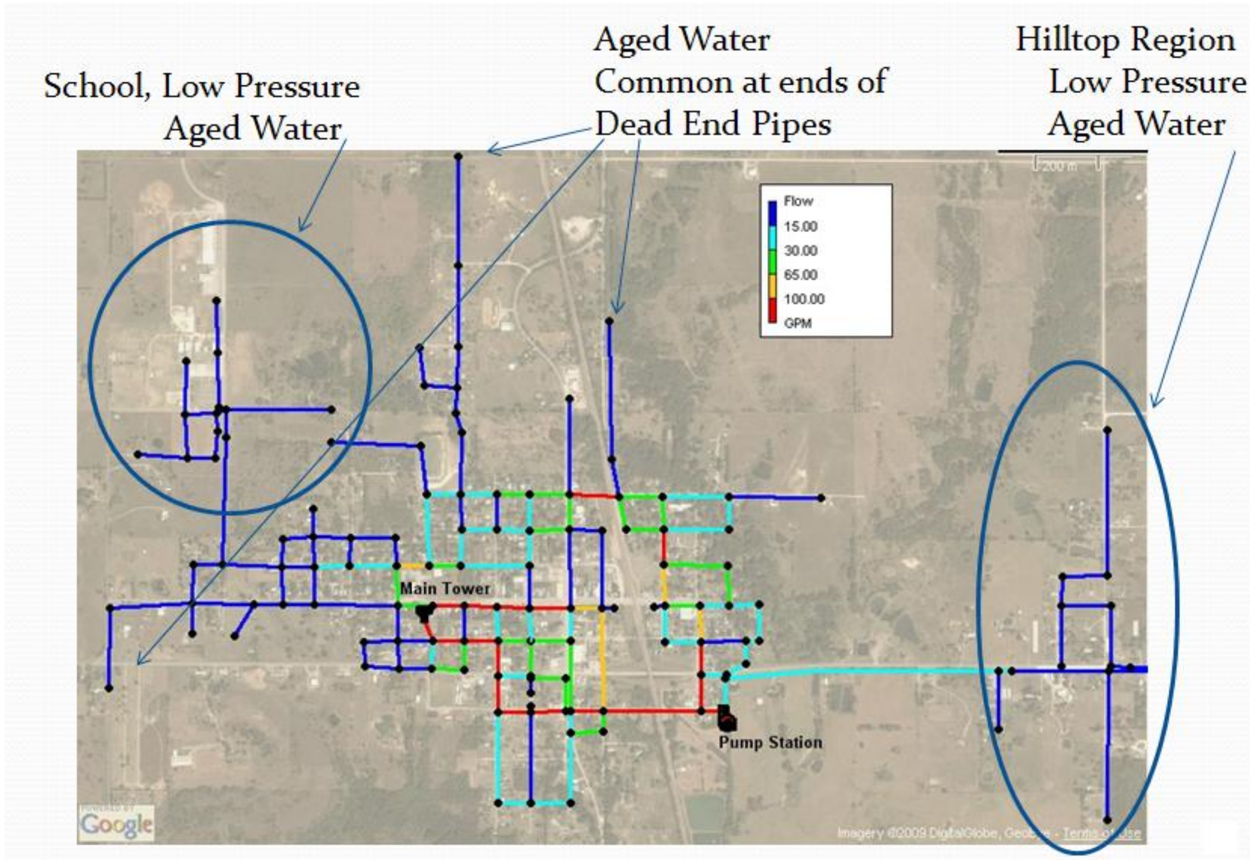

Figure 2. Digitized EPANET Model of the Water System for Beggs, Oklahoma Showing Pipeline Flow and Indications of Areas with Low Pressure and Areas Where Age of Water in the Pipes was Problematic.

The alternatives simulated to correct the problems shown in Figure 2 included installing new or modified pumps, a new water tower on the east end of town, replacing old pipes that had corrosive deposits, and / or adding new pipes to eliminate dead ends and create new water paths.

A set of simulations involving the addition of new pipes to convert the long single pipes shown in Figure 2 into loops indicated the problem of water age could be remedied most of the pressure and fire flow problems could be resolved. The pipes and water tower added during the simulations are shown in Figure 3.

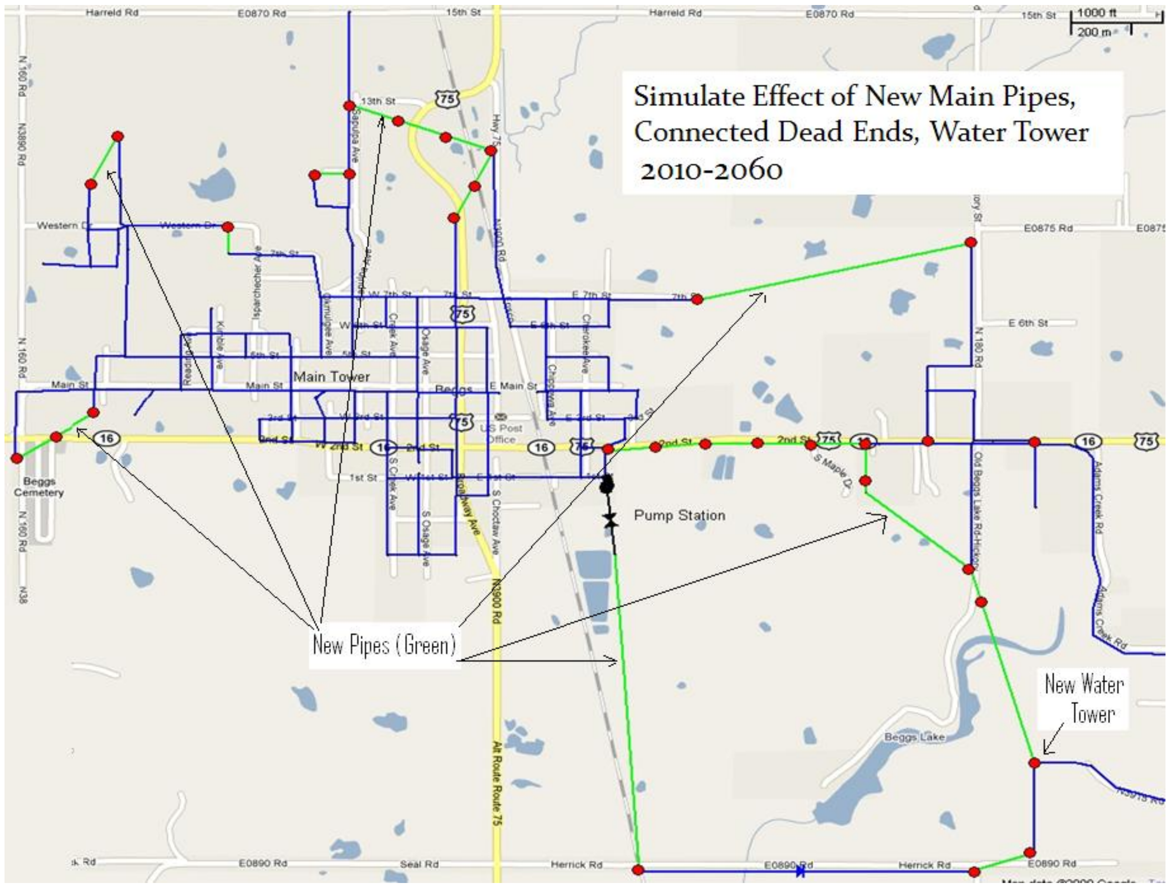

Figure 3. EPANET Model of the Water System for Beggs with Pipes added to Eliminate Dead Ends and the Location of a New Water Tower.

An important issue for a small town like Beggs, which is currently facing sewer upgrade problems, is the cost and the best order in which make modifications.

Cost estimates for pipe, pumps, and storage tanks were obtained from Means (2009) and adjusted were necessary to account for price changes since publication. Table 2 shows the prices used to the cost of installing PVC pipe of alternative diameters. A spreadsheet was used to develop the cost for the purchase and installation cost of alternative sizes of PVC pipe from 2 through 8 inches, using data on the cost of pipe, excavation, and backfilling used estimates from Means (2009).

Table 2. Costs Used for AWWA 160 SDR-18 PVC[a] Pipe, Trenching, and Backfilling

Diameter	Pipe	Trenching[b] and Backfill	Total Cost
Inches	$/LF	$/LF	$/LF
2	2.24	3.47	5.72
3	5.01	3.55	8.56
4	6.12	3.62	9.75
6	8.62	3.77	12.40
8	12.17	3.92	16.10

[a] Polyvinyl Chloride pipe.
[b] Assuming the pipe is placed in a two foot wide trench so the top of the pipe is 36 inches below the surface.

The problem of choosing the most economical diameter for single pipe to deliver a given volume with a designated head or pressure at the delivery can be determined by enumeration. For each diameter, add the annualized installation cost of the pipe to the annual cost of energy required to force the water through the pipe. Choose the diameter with the smallest annual total cost. Suppose it is necessary to purchase pipe that will deliver 100 gpm over a mile and up into an 80 foot tank. The amount of brake horsepower required is calculated as

$$\text{bhp} = \frac{\text{Head ft} * \text{GPM}}{(3960*\text{pe}*\text{me})},$$

where

pe is the pump efficiency, for example 0.7, and
me is the motor efficiency, for example 0.91.

If an electric motor is used, the amount of electricity used per year is 0.746 * bhp *8760 hours. The total feet of head required is equal to the 80 feet of lift into the tank plus the head (pressure) necessary to force 100 gpm of water through one mile of pipe of a given diameter. According to the Hazen-Williams formula, the head loss is,

$$\text{Hloss (ft)} = \frac{10.51\,(\text{GPM}/C)^{1.85}\ \text{Length}}{D^{4.87}}$$

Where

C is a Hazen-Williams friction coefficient, assumed to be 140 for PVC pipe
D is the inside diameter of the pipe in inches
Length is the length of the pipe.

The minimum annual cost involves a tradeoff between pipe size and energy cost. As the diameter of the pipe increases, the total cost of the pipe increases, but the energy required to force the water through the pipe decreases. A standard capital recovery factor was used to annualize the cost of the pipe. The annual capital cost for one mile of pipe (Table 2) and the annual pumping costs are added together in Figure 4. The least cost alternative is the four-inch diameter pipe that would cost $7,000 per year.

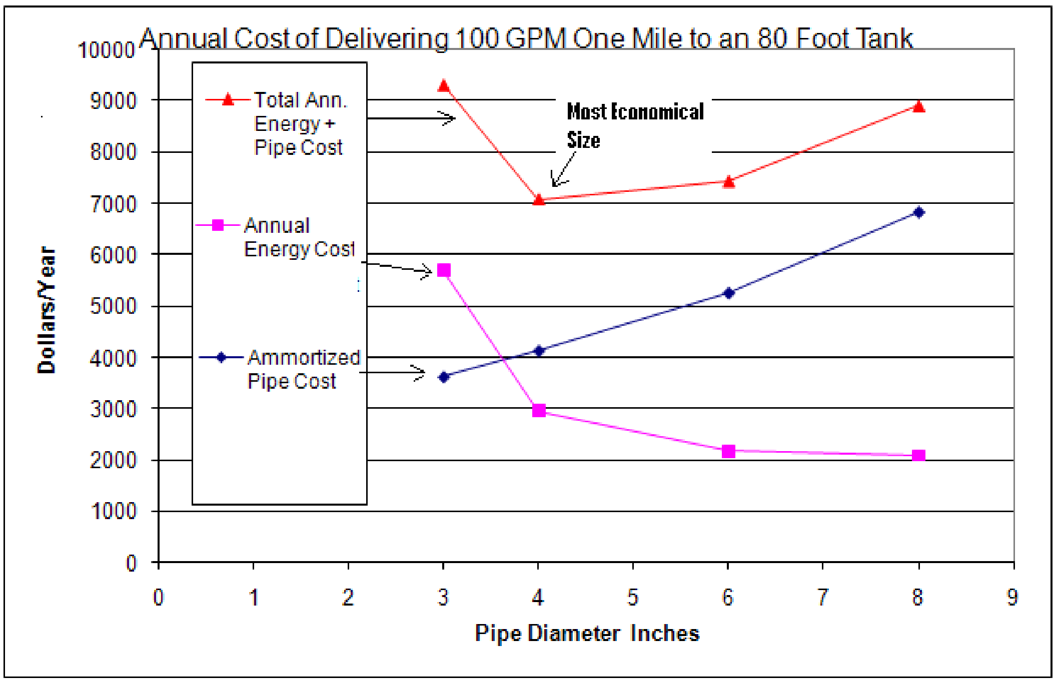

Figure 4. Comparison of Annual Total, Capital, and Energy Cost to Install One Mile of PVC Pipe with a 20-year Life to Deliver 100 GPM to an 80 Foot Tank when Electricity Costs are $0.10 per kwh and the Interest Rate is Five Percent..

However, in a water system the problem is more complicated since a new pipe will be used in a net work with other pipes. Also, Oklahoma mandates require that if a fire hydrant is attached to the pipe, the minimum diameter would have to be six inches. Alternative simulation runs were used to compare the system performance in terms of pressures and energy cost before and after each change in the distribution system infrastructure. The capital costs associated with different solutions were calculated outside the simulation.

The ability to meet fire flow requirements at each fire hydrant node was tested by adding a 250 gpm demand to each node in turn and testing the pressure after a two hour simulation. The full set of fire node tests were repeated after each set of infrastructure changes. Excel macros were again used to write out the simulation input data, run the simulation, retrieve the results of each simulation, and determine the number of fire flow and other failures in the system. A set of incremental infrastructure investments was developed that maximized the number of new fire hydrant nodes meeting the fire flow test per dollar spent. The results are shown in Table 3. In Table 3, the greatest initial improvement per investment dollar came from adding the two major pipes in the eastern part of Beggs. At the bottom of Table 3, the additional water tower in eastern Beggs, added onto the previous changes, had the fewest improvements per dollar spent.

Table 3. Order of Changes in Beggs Water Distribution System to Maximize Fire-Flow Compliance per Dollar Invested.

Order	Description of Changes	Cost
1	Install two major pipes in East Beggs	$ 69,000
2	Add three additional pipes in East Beggs to finish addressing Hilltop pressure problems	$ 60,000
3	Add remaining pipes to eliminate targeted dead ends	$ 57,000
4	Add Additional Fire Hydrants	$ 60,500
5	Add 50,000 gallon water tower in East Beggs	$ 167,000
	Total All Changes	$ 415,000

Site description of Oilton, Oklahoma

The City of Oilton is located in Creek County and is approximately 54.6 miles to the west of Tulsa. Located close to the Cimarron River, the city of Oilton houses a small community having a population of about 1200 people. The approximate area of the city is 0.65 square miles, which is about 416 acres. The City of Oilton receives its water supply through groundwater. The system has two wells that are located five miles to the south of the city. The storage facilities used by the town are two standpipe tanks. One tank is located outside the city and the other tank is located in the city. The exact age of the pipelines is not known. The main pipeline that brings water to the city is an eight-inch asbestos cement pipeline. There are two main distribution pipes in the town, one of which is an eight-inch PVC pipeline while the other is an 8 inch asbestos cement pipeline. All other mains and sub-mains are in the range of 1 to 6 inches. A summary of the statistics of the Oilton water distribution system is shown below in Table 5. Figure 1 shows the map of the town. Figure 2 shows a schematic of the distribution system.

Table 4: Oilton System Statistics

- Source: 2 deep (approx. 500 ft) wells
- Pumps: Single submersible pump per well
- Total Storage: 950,000 gal
- Pumping Rate: 118,000 gal/day (81 gpm)
- Population Served: 1200

Selection of hydraulic simulation software for Oilton, Oklahoma

The hydraulic simulation software used for this part of the study was WaterCAD V8i distributed by Bentley Systems. The aim was this project was to provide an economic tool which would be affordable to rural water districts. However, after completion of the previous study carried out for the Beggs water system, it was evident that the free hydraulic simulation software used (EPANET) was too sophisticated to be handled and updated by the rural water districts' staff.

Thus this project has a demonstration approach. WaterCAD V8i was selected due to ease of model building and operation and its greater programming capabilities as compared to EPANET. Although rural water system personnel are not likely to be able to use WaterCAD, most professional civil engineers do have knowledge of the software and a demonstration of its applicability to rural systems can potentially aid future efforts to assist these communities.

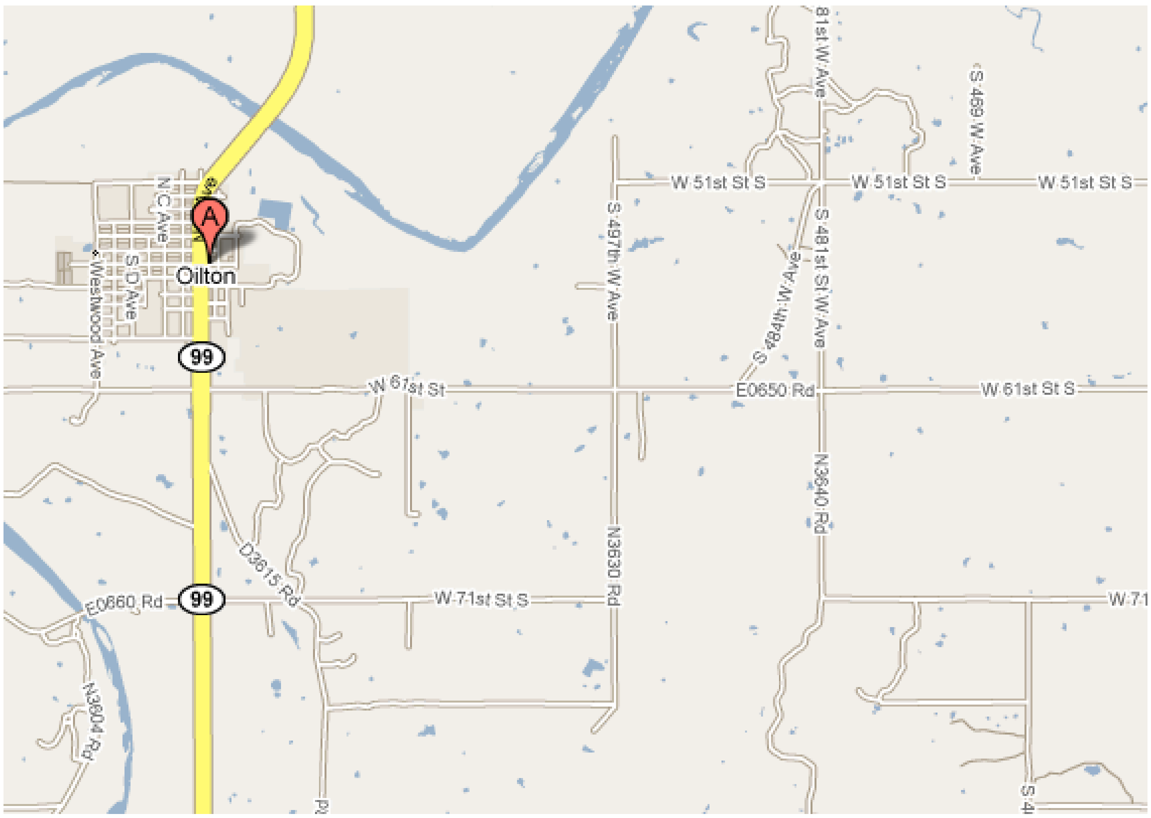

FIGURE 5: Map of Oilton, Oklahoma, Area (Google Maps, 2009)

To use the simulation software, the following steps were followed:

1. Pipelines were digitized, from information gathered on location (x-y coordinates), length, and diameter.
2. Facilities were located, including treatment plants, wells, pumps, and towers/standpipes.
3. Unknowns at this point included
    - Elevation Changes along pipeline
    - Location of Users along pipeline

- Demand allocation along pipeline
- Age, Condition, Materials

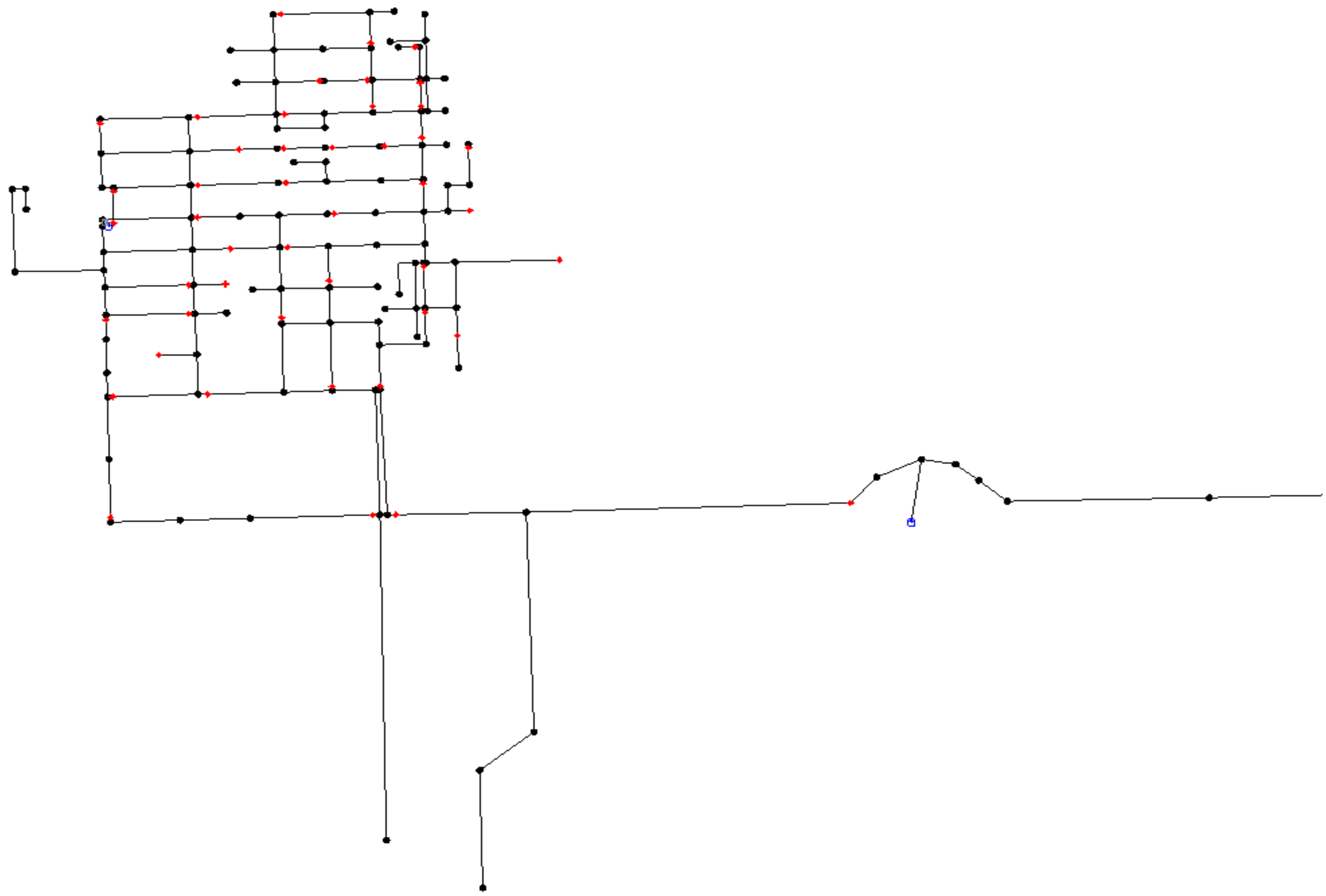

FIGURE 6: Schematic of Oilton, Oklahoma, Water Distribution System (Bhadbhade, 2009)

Apart from the preliminary information, additional inputs were required for the simulation of the model. The most important was the elevation dataset. Without the elevations, it is not possible to run the hydraulic simulation. The elevation dataset was obtained from the United States Department of Agriculture (USDA) website called the “Geospatial Data Gateway” (USDA, 2009). Note that this elevation data source is different than that used for the Beggs simulation. The second important dataset necessary was the information regarding houses in each census block. This information is required to assign base water demands to each node. The census block data was obtained from the US Census Bureau website called the "2008 TIGER/Line Shapefiles". The user can select the respective state and county, and the Census 2000 Block data was used to match households to potential nodes. Again, the USDA Geospatial data Gateway website was used to download the ortho-images of Oilton for identification of the houses in each census block.

Oilton Simulation Results

- Very large storage results in long water age and excessively long (several days) pump cycles to fill the tanks.
- However, most storage volume is unusable due to low pressures that result when water in standpipes is dropped more than 30 ft from the top of the tanks.
- Excessively long, low-demand lines result in high water age and low disinfectant residuals at dead ends.

Site description of Braggs, Oklahoma

Braggs is located in eastern Oklahoma, 56 miles south east of Tulsa (Figure 7). The population of the city is 308. The largest section of the existing water distribution system was installed in 1982 and has been serving the local population and 650 people in surrounding areas for the last 27 years.

BRAGGS, OKLAHOMA

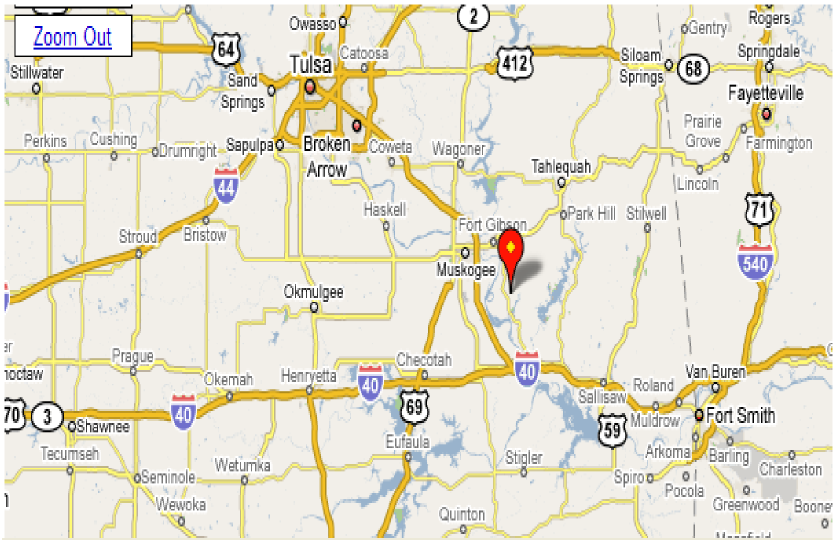

FIGURE 7: Map of the Braggs, Oklahoma, area (Google Maps, 2009)

Currently the system has 416 service connections and serves 1030 people from its primary water source which is ground water artesian wells. The distribution system network consists of three water towers; one located in the center, one at the north end and one on the south end of the city, giving a total storage capacity of 200,000 gallons.. A summary of the statistics for the Bragg distribution system is shown in Table 5.

Table 5: Braggs System Statistics

- Source: Artesian Wells
- Pumps: 3 identical working in parallel
- Total Storage: 200,000 gal
- Pumping Rate: 75,600 gal/day (52.5 gpm)
- Service Connections: 416
- Population Served: 1030

The piping consists mainly of long two inch branches pipes which are interconnected by a few four and six inch supply mains.

The map of the Braggs water distribution system was obtained from the Water Information Mapping System (WIMS) on the Oklahoma Water Resources Board (OWRB) website at http://www.owrb.ok.gov/maps/server/wims.php. WIMS is an Internet-based map server that requires a supported web browser. The Braggs system is shown in Figure 8.

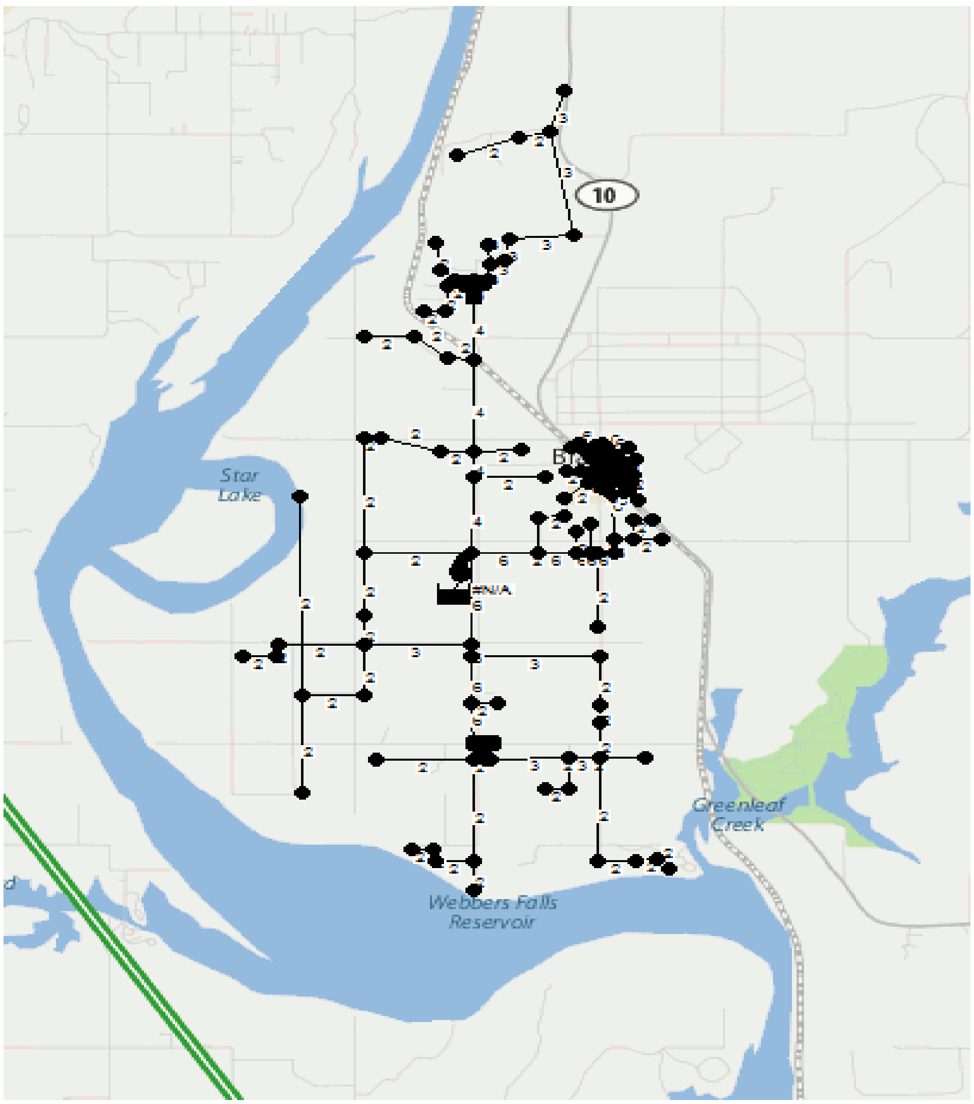

FIGURE 8: Schematic of Water Distribution Pipelines in Braggs, Oklahoma, Service Area from EPANETZ

Information regarding the age of the system, problems related to inadequate flows, low water pressure, leakages and bursts water usage patterns and equipment information for pumps was obtained from interviews with the plant operator at Braggs, Oklahoma. Water usage data were obtained from the Oklahoma Department of Environmental Quality (ODEQ) records. The records included information regarding the total water pumped daily from the treatment plant, the pH and the doses of the different chemicals added to the water prior to distribution over an eight year period from January 2001 to April 2009.

Hydraulic modeling using EPANET for Braggs, Oklahoma

The process of modeling a network using EPANET involves input of the parameters or variables that most closely describe the operation of the actual system. These parameters include the shape of the tanks, the pump curve which describes the operation of the pump and an infinite reservoir. Other input parameters required for the model to run include the maximum and minimum water levels and an initial water level in the tank. The three water tanks at Braggs are all cylindrical in shape.

There are three identical pumps at Braggs, each delivering 150gpm at 208ft of head. The pumps operate in parallel delivering the same head and are set to sequentially come on line in order to meet increasing flow requirements for the system. The pumps were modeled according to the information received from the system operator. Usually a single pump is switched on when the pressure drops below 65psi and is switched off when the pressure exceeds 80psi. Therefore, rule based controls were set within the EPANET model to ensure that the first pump was switched on when the pressure dropped below 65psi and switched off when the pressure increased to 80psi. Pump 2 was modeled to switch on if the pressure dropped further as would be the case in the event of a fire. Pump 3 was treated as a standby for the system in case pumps 1 or 2 failed to operate and was not included in the hydraulic modeling process.

The greatest percentage of the pipes at Braggs were installed in 1982 when the currently existing PVC pipes were installed to replace deteriorated cast iron pipes that had been previously installed in the 1940's. Therefore, most of the pipes are almost 30 years old. The operator noted that they had not replaced any pipes recently.

Braggs Simulation Results

- Technical work necessary to use the EPA Net software took several months. The software is not user friendly and technical support is non-existent.
- Relatively good records from the operator resulted in good match between simulation and the limited physical system measures (flows and pressures).
- Water age was high and disinfectant residual was predicted to be low in the long dead ends. Looping did not help, since it merely increased the flow paths and further lowered velocities.

Overall Project Conclusions

The project was successful in constructing a methodology to evaluate rural water system infrastructure. The incorporation of different water sources, infrastructure issues, and modeling software indicates that several approaches can be taken to effectively help rural water systems plan and update their water supply infrastructure. The development of a cost estimating methodology was also an essential part of the project, since understanding the costs associated with different upgrades is important for the community to understand. Highlights of the project results include:

- Small systems have common problems of low demand and long, low-velocity lines, which result in high water age and low disinfectant residual.
- The common remedy for high water age, which is to loop the pipes, does not always work for small systems, due to very low demand. A loop will add even more length to an already excessively-long system.
- Elevation differences mean that some areas have high pressures while others have very low (sometimes unacceptable) pressures.
- Technical expertise and experience necessary to use either EPA Net or WaterCAD are beyond the staffing capabilities of small systems. It took several months for engineering graduate students to become familiar with the software.
- Small communities need assistance in writing grants to get funding for system improvements. Just getting a grant written is beyond the capability of most system staff members.

To this last point, each of the communities participating in the project expressed anxiety about paying for the upgrades suggested by the simulations. Discussions with OWRB personnel indicate that significant effort has already taken place to educate rural water district personnel about requirements for applying for funding, including a multitude of fact sheets and even a yearly full-day conference sponsored by the Funding Agency Coordinating Team (advertised as "one stop shopping to find the financing you need for your project" (Oklahoma Rural Water Association, 2009)). Our experience suggests the promotion of this type of event is crucial, as is the technical help provided by "Circuit Riders" who travel to small water systems and provide educational sessions for system personnel. Finally, the need for professional engineering help indicates that an extension program (provided by any land-grant university) focused on this area would be in high demand, particularly for states with many rural water systems. Funding a full-time engineer to deal with projects such as those explored in this paper would provide significant benefit for the rural water systems assisted and would likely result in extremely positive publicity for the departments involved.

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