Physical Model Analysis Report

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368 N. Hwy 27

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UNIVERSITY OF KENTUCKY

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Craig Ashby
Matthew Jolly
Scott Yost

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Executive Summary

There is an increasing trend toward the use of computer models to represent the operations of a water distribution system, moving closer to the goal of utilizing a model in real time. In order to meet this goal, a model must be able to represent the system as accurately as possible with regard to hydraulics and water quality. A physical model of a skeletonized medium-sized water distribution system has been built in the University of Kentucky hydraulics laboratory with the purpose of investigating the accuracy of hydraulic and water quality models. The physical model contains a reservoir, a pump, and three elevated storage tanks. It is equipped with pressure sensors, flow meters, and tank level meters to monitor the hydraulic boundary conditions of the network, as well as electrical conductivity meters to monitor the water quality of the network. All these sensors are fed to a single data acquisition system.

This document presents the results of the experimental work performed on the network, and makes comparisons between the hydraulic and water quality models. Two different methods of calibration are presented. The first method accounts for all the components that contribute to minor losses in the network. The second method utilizes calibrated frictional loss coefficients that are intended to represent both the frictional and minor loss components of the network. This is referred to as a "lumped C-factor," and is the method of calibration that is typically employed in full-scale water distribution systems.

The hydraulic and water quality results of the models all predicted the observed data of the network with reasonable accuracy. Furthermore, neither method of calibration consistently produced a more accurate model than the other. Both calibration methods, however, show that there is still room for improvement. In the physical model, the minor losses contribute to a larger portion of the total losses than they do in a full-scale water distribution system. Therefore, in order to create a more accurate model, it may be necessary to determine the minor losses of the network by experimentation rather than using the typical literature values. In a full-scale water distribution, it may be sufficient to calibrate the model using a lumped C-factor approach. This method of calibration is more practical than attempting to model every component that creates an energy loss in the pipelines.

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Introduction

The hydraulic pipe network and monitoring system was designed and constructed to function as a skeletonized model of a medium-sized water utility. The goal of the research was to examine and compare hydraulic and water quality model performance with controlled experimental lab data in multiple scenarios. There are an unlimited number of different scenarios and conditions that can be placed upon the model network. Therefore it was critical to maintain consistency in the methodology and use of the system to ensure the repeatability of experiments, the integrity of the equipment, and the quality of the experimental data and results.

The methods and information presented in this report represent the general guidelines and procedures utilized for the research work for maintaining quality and repeatability of experiments within the laboratory. The methodology does not represent a comprehensive procedure or protocol for every possible experiment that can be conducted using the physical model setup and data acquisition system. The procedures and protocols utilized for the research were developed with the intent of examining the performance of hydraulic and water quality models.

A brief overview of the physical model set up and components is presented within this report. A full treatment of the physical model can be found in the previously published *Physical Model Design and Construction Report* (Ashby and Jolly, 2011). Discussion and presentation of the experimental procedures require a brief review and overview of the physical model setup in the context of experimental work.

There is a brief discussion of the statistical methods utilized for research work. The data sets for each experiment were examined for trends, non-normality, and non-constant variance. It was found that if sufficient time was allowed for a network to stabilize to a steady state, the data would be free from non-normality and non-constant variance in the instruments. This indicates the instruments are operating normally and free from non-random biases. It is also required that pressures throughout the network were sufficiently above 0 gage pressure to ensure against non normality and non-constant variance in the instruments dataset for an experiment.

Experimental Methodology

This section discusses the aspects involved with implementing and modeling an experimental setup. It documents the calibration of the instruments, hydraulic calibration, general experimental procedures, and the development of the computer model for hydraulic and water quality modeling.

Instrument Calibration

There are four different types of instruments implemented in the physical model: tank level meters, flow meters, pressure sensors, and electrical conductivity meters. They each output a current between 4 and 20 mA, which corresponds to a value of the parameter they are intended to measure. Therefore, each type of instrument has a slightly different method of calibration. The end result of each calibration is an equation that takes the instrument’s current as an input; these equations are subsequently programmed into the LabView development environment so that each virtual instrument outputs the correct units of measurement (LabVIEW, 2012).

Tank Level Meter Calibration

The tank level meters are *Echosonic II* ultrasonic level transmitters (Echosonic, 2012). These units include a USB drive, which lets the user connect the device with a PC. The device utilizes the *WebCal* software, which allows the user to calibrate the instrument by inputting the sensor height and overflow height relative to the bottom of the tank (WebCal, 2012). The software then calibrates the instrument to output 4 mA when the tank is empty and 20 mA when the tank is overflowing. Knowing the minimum and maximum tank levels as well as the minimum and maximum output signal, the user can then input a linear equation into the LabView environment to convert from an ampere output to a tank depth in inches. The elevated tanks usually fill to a depth of 12 to 30 inches, but are largely dependent on the conditions of the network. According to the manufacturer, the tank level meters operate with an accuracy of ±0.2% of the operational range. Table 1 shows the maximum tank level, accuracy, and the calibration equation for each tank, where H is the tank depth in inches and A is the instrument output in amperes.

Table 1: Tank level meter calibration

Tank	Overflow Depth (inches)	Sensor Height (inches)	Equation	Accuracy (inches)
T-1	32.250	38.625	$H = 2015.6A - 8.0625$	±0.081
T-2	32.500	38.500	$H = 2031.3A - 8.1250$	±0.081
T-3	33.250	38.375	$H = 2078.1A - 8.3125$	±0.083
Reservoir	69.750	75.500	$H = 4362.5A - 17.4500$	±0.175

Flow Meter Calibration

The flow meters used in the model are *Clark Sonic* ultrasonic flow transmitters, which are factory calibrated to output a linear relationship between amperes and flow rate (Clark Sonic, 2012). Each size of flow meter (1”, 1.5” and 2”) has two options for the range of flow rates that it can read. Since they all output 4 mA to 20 mA, each size and range requires its own equation to translate amperes into the flow rate in gallons per minute. All the flow meters were set on the high range except for the flow meters that measure the inflow and outflow of the elevated tanks. The pipes connected directly to the tanks typically have a lower flow than the pipes that supply and drain the remainder of the system. According to the manufacturer, the flow meters are accurate to ±0.75% of the full scale output (Clark Sonic, 2012). Table 2 shows the size, range, equation, and accuracy for the settings that were used in the model. The only 1.5” meters are on the transmission lines, which always have the highest flow rate in the system; therefore, the low range setting was not used for these meters. The remaining flow meters typically experience flow rates between 1 and 30 gpm, depending on the location of the meter in the network.

Through the experimentation and modeling process, it was determined that the flow meters on the transmission lines tend to overestimate the global flow of the network. Therefore, only the flow meters at the outlets should be used to estimate the flow. This discrepancy is discussed in more detail in the Steady State Hydraulic Analysis 5 portion of this document and verified in each steady state analysis case.

Table 2: Flow meter calibration

Pipe Size	Low/High Range	Minimum Flow rate (gpm)	Maximum Flow rate (gpm)	Equation	Accuracy (gpm)
1”	High	0.75	50	$Q = 3078.1A – 11.5630$	±0.46
1”	Low	0.45	30	$Q = 1846.9A – 6.9375$	±0.28
1.5”	High	1.2	80	$Q = 4925.0A – 18.5000$	±0.74
2”	High	1.8	120	$Q = 7387.5A – 27.7500$	±1.11
2”	Low	0.9	60	$Q = 3693.8A – 13.8750$	±0.56

Pressure Sensor Calibration

The pressure sensors used in the model are *Noshok* pressure transducers, which are factory calibrated to output 4 mA to 20 mA, which linearly corresponds to 0 to 30 psi (NOSHOK, 2012). The linear relationship is shown by eq. 1, where P is the pressure in psi and A is the current output from the instrument in amps. Typically the sensors will experience 2 to 8 psi throughout most of the system, and about 18 to 20 psi near the pump. They are accurate to ±0.25% of the full scale output, which translates to ±0.094 psi. Since all the sensors are the factory calibrated and have only one output range, no additional calibration work is needed.

$$P = 1875A - 7.5 \qquad \text{Eq. 1}$$

Conductivity Meter Calibration

G.F. Signet electrical conductivity meters are used in the model to determine the concentration of a calcium chloride tracer that has been injected into the network (George Fisher Signet LLC, 2010). The meters output 4 to 20 mA of current, which correspond linearly to one of 80 possible ranges of electrical conductivity. Each instrument has a cell constant determined by the manufacturer, which accounts for a slight variability in the area of the probe that comes in contact with the water. The cell constant is multiplied by the electrical conductivity value in µS/cm, as determined by the linear regression between amps and conductivity. Since tap water is used in the model, the water in the system has a background conductivity. Therefore it is necessary to set the conductivity meters to be able to read within the range of the background conductivity, but on a small enough scale to detect minor changes in conductivity due to an increase in calcium chloride. Using the conductivity meters, the electrical conductivity of tap water was found to be approximately 399 µS/cm. Thereafter, the meters were set to read 0 to 1000 µS/cm. Because the maximum conductivity is set at 1000 µS/cm, the maximum concentration is approximately 0.27 g/L. Therefore, as the background concentration of calcium chloride in the system rises, the reservoir eventually will need to be drained and filled back up with tap water.

The relationship between amps and calcium chloride concentration was determined experimentally for each electrical conductivity meter. Each meter was used to measure the electrical conductivity of five different known solutions of calcium chloride. A linear regression was created for each meter and programmed into LabView to obtain results in units of concentration of calcium chloride. Table 3 summarizes the results of this calibration procedure. The accuracy of each instrument was determined based on the manufacturer’s specification that

Table 3: Electrical Conductivity Calibration: meter output in amps

	Meter					
Concentration (g/L)	A	B	C	D	E	F
0	0.010336	0.010471	0.010339	0.010447	0.010387	0.010227
0.058	0.013265	0.013395	0.013225	0.013287	0.013199	0.013277
0.108	0.014951	0.015162	0.014947	0.01482	0.014677	0.01505
0.199	0.017521	0.01794	0.017582	0.017312	0.017536	0.017447
0.24	0.018863	0.019074	0.018767	0.018831	0.018861	0.019058
Instrument Cell Constant	1.005	0.992	1.006	1	1.006	1.009
Conductivity (tap water, μS/cm)	397.9612	401.2103	398.5772	402.9521	401.6099	392.7175
Accuracy (g/L)	±0.0115	±0.0128	±0.0120	±0.0095	±0.0120	±0.0130
Equation	$C = 28.897A - 0.3121$	$C = 28.276A - 0.3090$	$C = 29.000A - 0.3132$	$C = 29.688A - 0.3225$	$C = 29.018A - 0.3123$	$C = 28.196A - 0.3023$

each instrument has an accuracy of 2% of its output span in μS/cm. These errors were transformed into units of g/L using each instrument's cell constant and regression equation.

Computer Model Development

System Configuration

An EPANET (Rossman, 2000) and KYPIPE (KYPIPE LLC, 2010) model of the physical model was created to compare the results of the lab model with the results of the computer model. The model uses the inside diameter of each pipe size, as measured using calipers and compared to manufacturer's specifications. All the lengths of pipe, elevations of nodes relative to the floor of the lab, and tank elevations have been measured and input into the model. The C-factors have been determined by the calibration using a lumped parameter approach typically used in water distribution system modeling. Figure 1 shows the EPANET schematic of the system.

The reservoir and pump in the top right corner of the schematic represent the injector pump with the calcium chloride solution being injected into the system. The line connecting the outlet of the injector pump to the network can be moved to any node in the network. This line is initially open with a control placed on it, causing it to close after a user-specified duration of injection. Since the network recycles water rather than pumping in fresh water, the background electrical conductivity slowly rises as the calcium chloride solution is being injected, making the conductivity sensor readings incomparable with EPANET's modeled water quality results. To remedy this problem, an electrical conductivity meter is placed in the tee immediately downstream of the pump, upstream of the injection point. This constantly measures the background concentration of calcium chloride; the final concentration is used as an input for the source quality of the reservoir in the EPANET model. The measured concentration at each time interval was divided by the final measured concentration, giving a time series of coefficients that were input into the model. EPANET uses these coefficients to scale the input concentration, giving the correct background concentration throughout the simulation.

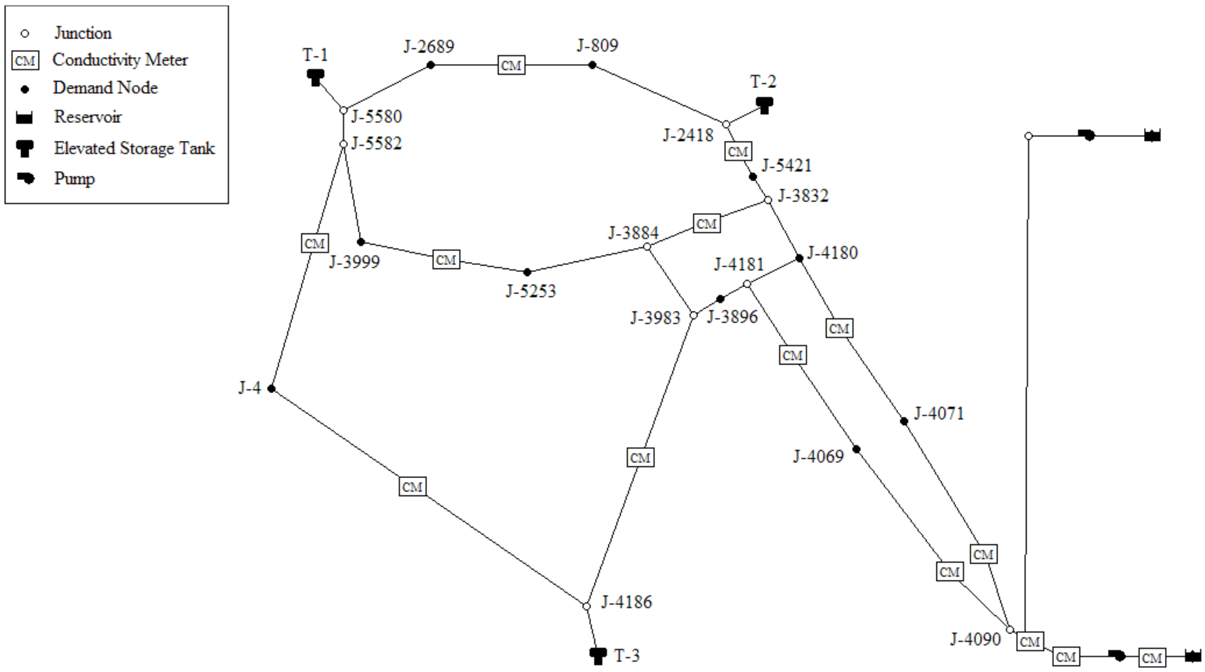

Figure 1: EPANET Schematic (not to scale)

Pump Calibration

The pump used to supply water to the network is a 3 horsepower *Grundfos* end-suction pump ("Performance Curves," 2011). The manufacturer supplied the head/discharge curve shown by eq. 2 for this model of pump.

$H = -0.0015Q^2 + 0.0107Q + 67.5$ Eq. 2

A new pump curve has been determined experimentally. This was done by first placing a pressure sensor in the pump housing, and then closing off the pipes that feed the storage tanks. Using this configuration, all the flow through the pump is exiting the system via outlets that are equipped with flow meters. The system started with all valves open; pressure and flow data were collected for the system, and subsequently averaged. Next, the outflow valves were closed until another distinct pressure and flow condition was obtained. Once again, pressure and flow data were taken and averaged. This process was repeated until a series of data was obtained to represent the pump's full range of operation. The pressure data was converted from psi to feet of head; a second order polynomial was fit to the data using a least squares regression. This regression was then used as the new pump curve for the model. Table 4 shows the data from the pump calibration. The new equation results in the modeled cutoff head increasing by about 6 feet. The new head/discharge curve is:

$H = -0.0017Q^2 – 0.073Q + 73.465$ Eq. 3

Table 4: Pump performance data

Flow (gpm)	Pressure (psi)	Head (ft)
116.33	17.99	41.52
114.94	18.45	42.57
101.84	20.97	48.40
75.84	25.74	59.40
70.21	26.41	60.95
64.63	27.01	62.33
57.32	27.47	63.39
50.72	28.04	64.70
43.05	28.82	66.52
35.90	29.32	67.66
28.66	30.00	69.23
20.26	30.88	71.26
14.00	31.41	72.48
7.78	31.93	73.68

C-Factor Calibration

A C-factor calibration was performed on the network in an attempt to quantify the energy losses due to friction. This was done by closing off pipes in the network such that the water could only flow through one path of similar sized pipes, leading to a separate C-factor for each of the three pipe sizes. Since each junction in the experimental setup contains a pressure sensor, and each outlet contains a flow meter, all the parameters for the calibration are known. The Hazen-Williams equation was used to determine the C-factors:

$$C=\left(\frac{4.52LQ^{1.854}}{\Delta Pd^{4.87}}\right)^{\frac{1}{1.854}} \qquad \text{Eq. 4}$$

L = Length (ft)
Q = Flow rate (gpm)
ΔP = Pressure drop (psi)
d = Diameter (in)

The following table shows the C-factors that were found using this approach for each pipe size:

Table 5: Calibrated C-Factors

Nominal Diameter (in)	C-Factor
1	118.99
1.5	127.53
2	135.13

Table 6: Typical Minor Loss Coefficients

Component	***Minor Loss Coefficient***
Ball Valve (fully open)	0.05
180° Bend	0.2
90° Elbow	0.2
45° Elbow	0.2
Coupling	0.02
Reducer (2"-1")	0.5
Reducer (1.5"-1")	0.2
Tee	0.2

Minor loss coefficients

All the components of the model that contribute to the minor losses of the system have been enumerated, and their corresponding minor loss coefficient has been estimated using literature values (see table 6).

Steady State Hydraulics

To simulate a contamination event, the first step is to plan the general configuration of the network. Each pipe can be turned on or off using a ball valve so that the model can reflect the desired configuration. The injection point and contaminant observation point should also be predetermined so that the electrical conductivity meters and injection pump can be moved to the desired locations before flowing water through the network. These can be inserted into the ¾" threaded connections throughout the system. A check valve can be placed in the in any of the ¾" connections at the point of injection to prevent any backflow from the system pressure.

Once the configuration is set up, the model needs to reach a steady state condition. This is done by turning on the pump and incrementally turning the gate valves at each outflow junction until the water level in the tanks start to rise. If one of the tanks starts to overflow, a network outlet on a pipe adjacent to that tank pipe may need to be partially opened to decrease the flow to the tank. Conversely, if a tank is empty, a nearby network valve may need to be partially closed to increase the pressure in that portion of the system, thereby increasing the water level in the tank. The best way to determine whether the system has reached a steady state condition is to observe the water levels in the tanks. When the level in each tank is neither increasing nor decreasing, the system has reached steady state. The system typically requires approximately two hours to reach steady state, depending on the configuration of the system.

Tracer Injection

While the system is reaching steady state, an injection solution should be mixed. Calcium chloride is used as the tracer to increase the electrical conductivity of the water. It can be purchased in the form of calcium chloride dihydrate, which consists of one part calcium chloride to two parts water. This equates to 75.5% calcium chloride by volume. The sensors can detect up to 0.27 g/L of calcium chloride. After every tracer injection, the background concentration of the system rises. Therefore it is important to inject a mass of calcium chloride that is high enough to detect, but low enough to keep the background concentration below 0.27 g/L.

When setting up the injection scenario, a three-way valve should be threaded into the check valve at the injection point. One of the ports of the three-way valve will always have flow through it, while the lever controls which of the remaining two ports is on. The port that always receives flow should be attached to injection pump hose via a barb fitting and hose clamp. The remaining port will be used as the bleeder port and will be connected to another barb fitting and hose, which discharges to an initially empty bucket. The suction hose of the injection pump should be fully submerged into a bucket of the calcium chloride solution. This injection procedure requires at least two people; at least one person should be at the point of injection and near the injection pump, and the other person should be at the data acquisition system. The person at the data acquisition system needs to monitor the output from the conductivity meters; if any of them are outputting a concentration less than zero, the person at the injection point should unthread the problematic meter until water starts to flow out of the port. This is done to release any entrained air that builds up around the sensor probe. Once the conductivity meters are all reading above zero, the injection pump can be turned on. At this point, the three-way valve should be set such that the injection pump discharges the solution into the empty bucket. When all the water that is contained in the hose has been bled into the bucket, three actions need to be performed simultaneously: the LabView data acquisition should be started, the lever on the bleed valve should be switched to flow into the system, and a stopwatch should be started. This is all to ensure accurate timing of the injection. While LabView has a ten second delay before displaying any data, it starts to store data immediately when the start arrow is clicked. When the desired amount of solution has been injected into the system, the timer should be stopped and the lever on the bleed valve should be switched simultaneously. The data acquisition should be stopped only when the reading at each conductivity meter has leveled out. A graduated cylinder should be used to measure the volume of water that is remaining in the two buckets such that the difference between the original measured volume and the remaining volume is the amount of solution that was injected into the system.

Statistical Analysis of Data

Overview of the Statistical Analysis

The goal of the research is to examine the performance of water quality and hydraulic algorithms in comparison with experimental data from a physical model of a water distribution system in a controlled laboratory environment. The objective of the research requires reviewing and analyzing experimental data from multiple scenarios. When analyzing the work of any experiment, it is important to properly analyze the data and consider various sources of errors. It is also important to determine if the instruments are operating within the established specifications from the manufacturers. Furthermore, it is important to determine the degree of confidence in measurements based upon the combination of instrument errors and general experimental errors. The degree of confidence for the averages of the pressures, flows, and tank levels indicate the precision of the average measurement.

Statistical analysis will be used to verify if a given experiment is operating at or very near steady state equilibrium. Ideally at steady state equilibrium, the time series data should be in a normal distribution about an average value, with constant variability, and with no trend over time. The statistical tests are being utilized as quality indicator of the experimental scenarios and data collected. Non-normality in the data and non-constant variance in a dataset are indications of possible issues with either the measurement device or some disequilibrium in the physical model away from steady state. Most likely the instrument is near the extremes of its measurement capability range or insufficient time was allowed for the network to reach equilibrium. This section of the report briefly discusses the procedures and methodology for determining normality in the data, de-trending the data, and analyzing non-constant variance in the experiment.

Testing for Trends in Experiment (Verifying Steady State)

The time series for each of the instrument classes (pressure, flow, and tank level meters) was analyzed for trends in the data. Ideally, the network remains in steady state equilibrium during each of the tests. However there were typically very mild trends in most of the instrument readings. The basis for determining the presence of a trend in a time series was the Fisher test statistic (Dielman, 2005), given as:

$$F=\frac{MSR}{MSE}=\frac{\Sigma\left(y_{predicted}-\bar{y}_{average}\right)^2/(\text{number of dep variables})}{\Sigma\left(y_{predicted}-y_{measured}\right)^2/(\text{number of samples-2})} \qquad \text{Eq. 4}$$

The test is a comparison between the prediction line that minimizes the square of the difference between predictions and measured values and the constant line equal to the average value on the x-y plane. The divisors in the two sums represent the respective degrees of freedom for the regression. Since the only dependent variable of interest is time, the number of dependent variables is one in the numerator. The number of sample points varies from test to test. The minus two represents the fact that it takes a minimum of three points to distinguish between the presence of a very mild linear relationship with a dependent variable versus a constant value with some unknown perturbed (plus or minus random variable) error and no relationship with a dependent variable. Hence two points are lost in the degrees of freedom for sum of the errors term. The hypothesis test (eq. 5) for determining the lack of a trend is that the slope (B_1) for the regression line is zero or very near zero, namely,

$$H_0: B_1 = 0$$
$$H_a: B_1 \neq 0$$
$$\text{Reject } H_0 \text{ if } F > F(\alpha;1,\ n\text{-}2) \quad \text{Do not Reject } H_0 \text{ if } F \leq F(\alpha;1,\ n\text{-}2) \qquad \text{Eq. 5}$$

The alpha in equation 3 is the percentage level of confidence for the test subtracted from one hundred percent. The $F(\alpha;1,\ n\text{-}2)$ term represents the critical value derived from the Fisher statistical distribution for the degrees of freedom. The critical value is the value for which a tail area no more than α percent lays outside that value. The selected level of confidence for the purpose of the research was 95% and thus alpha was 5%. The test was performed within an Excel spreadsheet using the FDIST function command for each time series in an experimental setup. When analyzing the data for the experiments, there tended to be very mild trends present in most data sets.

Any trends for each retrospective data series were removed from the individual time series by adjusting the data based on the linear trend slope and the distance from the average value for each time series. This was done so that the data and statistics from the experiment could be compared with future experiments. For example comparing statistical properties such as standard deviations, normalized standard deviations and testing for constant statistic properties in each measurement type. This will make comparisons more relatable since each “steady state” will tend to have very mild trends present in each measurement device and unique to that particular experiment. In addition, removing the trends from the dataset reduces the standard deviations of the adjusted datasets and reduces any bias made in a test for normality.

Testing for Normality (Verifying Normal Operation of Sensors)

Normality in the data was determined by examining the standardized residuals. The residuals are the measured data points minus the regression predicted data points as a function of time. The residuals are standardized by dividing by the standard deviation of the dataset. If the data collected is approximately normal, then 68% of the standardized residuals should be between -1 and 1. Also if the data is approximately normal then about 95% of the standardized residuals should between -2 and 2. Similarly, 99% of the standardized residuals should be between -3 and 3 for approximately normal data. The 68/95/99 rule for the standardized residuals should be fairly tight and within a few percentage points. Having a larger amount of the standardized residuals within the plus or minus one bin usually indicates a trend in the data. If data with a trend over time is considered constant about the data's average but with some general experimental errors, higher standard deviation estimates will occur and thus understate the standard residuals. The 68/95/99 rule was found be true for the de-trended flow data, tank level data, and pressure measurements; each appeared to meet the normality assumption.

The basis of testing normality was the regression line for the de-trended time series. Ideally, after de-trending the dataset for any upward or downward trend in the almost fully steady state equilibrium, the slope will be zero, or very near zero. For the cases examined for hydraulic calibration, the vast majority of instrument variance was found to be operating as a normal dataset. Non-normality in a dataset can indicate poor performance in an instrument or that the network still has some disequilibrium away from steady state. If the instrument and data collection system is operating properly the data collected should be normal after removing any trends.

Testing for Non-constant Variance

Ideally, the time-series for an instrument in a given steady-state experiment should have a constant variance about its average value over the interval of data collection. The presence of non-constant variance in a time series most likely indicates some disequilibrium in the network and deviation from true steady state network conditions. It may also indicate issues with the sensor. Non-constant variance in an instrument is a potential problem since it skews statistical tests and adds greater uncertainty to measured averages for given experiment. Furthermore, it makes determining the presence or absence of a trend more difficult.

A check was made to determine if there existed a non-constant error variance over time. There are several statistical tests for non-constant variance. The one used in the research was the Szroeter test, shown by equation 6 (Dielman, 2005). Allowing for a longer time period for a steady state to be reached greatly increased the performance for both normality and non-constant variance in a given experiment's data. Experiments in which the network was allowed to reach steady state over the course of a few hours were not found to meet the test statistic for rejecting the constant variance assumption. Therefore the variance can be said to not be increasing over time for the majority of instruments.

$$Q = \left(\frac{6*n}{n^2-1}\right)^{1/2}\left(h - \frac{(n+1)}{2}\right) \qquad \text{Eq. 6}$$

$$n = \text{ the number of data points for timeseries}$$

$$h = \frac{\sum_{i=0}^{n}\left(i \times \hat{e_i}^2\right)}{\sum_{i=0}^{n}\left(\hat{e_i}^2\right)}$$

$$\hat{e_i}^2 = (\text{predicted value} - \text{measured value})^2$$

As stated, for the tests and scenarios examined, if sufficient time was allowed to reach steady state equilibrium the instruments did not indicate any issues with non-constant variance within their establish measurement ranges. This indicates the measurement instruments are performing well and within specifications and is an indicator of quality in the collected data if sufficient time is allowed to reach equilibrium. This methodology was followed for the research work as it progressed for both steady state and water quality simulations. This was done in the analysis of scenarios presented in this report with the exception of case 6/4/2012.

Utilizing Eq. 6 requires ordering the data in increasing rank for the dependent variable. The data series is already naturally ranked in order of increasing time and thus no ordering was necessary. The sum of the squares of the residuals times the rank in order of increasing explanatory value divided by the sum of squares of the residuals is the value for h. If the Q test statistic is outside the boundaries of the Z values from a standard normal table with upper area alpha for either side of the normal curve then the assumption of constant variance can be rejected. The Z values are the ordinates for the standard normal distribution (mean of 0 and standard deviation of 1) with a given probability within the ordinates. The Z values for 99.99% confidence are -3.719 and 3.719 respectively, with 99.99% of the standard normal distribution within those bounds. If the Q value is within that range, the hypothesis of constant variance hypothesis can't be rejected. Outside those bounds, the data can be assumed non-constant with 99.99% confidence.

Steady State Hydraulics Analysis Overview

The hydraulic pipe network and monitoring system was designed and constructed to function as a skeletonized model of a medium-sized water utility. In order to compare the hydraulics of the network with the results of a hydraulic model, four different steady-state scenarios have been set up. This section of the report discusses the four test cases and compares their hydraulic data with the results obtained from hydraulic software such as KYPIPE. Each scenario was modeled three different ways. The first two methods utilize the typical literature values to estimate the frictional and minor losses of the network. Of these two methods, the first uses the raw data from the flow meters to determine the magnitude of the demand at each outlet. For the second method, the demand at each outlet was adjusted so that the global flow of the network matched the flow readings from the transmission line flow meters. For the final method, the lumped C-factor was employed to represent both the frictional and minor losses. The raw demand data were used for this final method.

The performances of the four KYPIPE models are presented in table 7 for the three different modeling methods. The four cases are discussed in more detail in the individual experiments report sections. The water distribution models performed to a high degree of correlation for a variety of different experiments. As previously mentioned, the 6/4/2012 model had some issues with non-constant variance for some of the instruments in the network. This issue was mainly due to not allowing sufficient time for the network to equalize. In spite of these issues, the corresponding KYPIPE model agreed with the experimental data to a high degree of probability.

The high correlation for the measured to modeled pressure for each of the experiments, despite some of the disequilibrium and mild trends in some of data, indicates that real time modeling about a hydraulic calibrated network model is feasible. Following the discussion of the

Table 7: Steady state modeled pressure to measured pressure comparison

Experiment	Demand Data Model	Adjusted Demands Model	Lumped C-Factor Model
1	100.17%	101.95%	99.01%
2	101.75%	102.16%	101.07%
3	100.83%	101.36%	99.85%
4	100.54%	100.48%	114.42%

four steady state scenarios, the investigation into the flow discrepancy is presented. The flow discrepancy exists between the flow transmission lines downstream of the pump and the sum of the ten outlet demands in the physical model. This issue was investigated to ensure that the flow meters at the demand nodes should be used versus a weighted average to correct the mass discrepancy. The flow was measured in several setups by physically measuring the weight of the water over an interval of time at a constant flow rate. The weight was measured downstream of the outlet line of pipe which is downstream of the outlet demands where the water is physically returned into the reservoir. In addition, as table 7 illustrates, the flows were adjusted by minimizing the relative change in each flow measurement average to create a flow mass balance. The results of the four cases show that using the demand flows at each outlet gives a model that more accurately represents the measured pressures of the network. The results of the investigation into the flow balance also shows that the demand flow measurement are more accurate than the flow transmission meters.

Steady State Hydraulics Analysis 1 (6/4)

Overview of the 6/4/2012 Experimental Setup

For this experimental setup, all the pipes, tanks, and demand valves in the network were open. The demand node gate valves were adjusted as described in table 8 to ensure that all the demands had a significant amount of flow. The experimental setup was run with the tanks initially full while the valves were set. Once set, the valves were unaltered and the network was allowed to run for a three hour period of data collection. The experiment was run for a long period of steady state equilibrium to look for any abrupt changes in flow or tank levels due to mild changes over a longer length of time. Figure 2 shows the KYPIPE schematic for this setup.

Statistical Analysis for 6/4/2012 Experiment

A least squares regression analysis was performed for the flow meters, tank level meters, and pressure meters datasets over the duration of the test period in an attempt to verify that the analysis period was at steady-state equilibrium. It was discovered that there tended to be a mild statistical trend in the dataset according to a Fisher test statistic. The methodology is as described in the statistical analysis section of the report was followed for performing the Fisher test. The experiment reached steady state equilibrium after approximately 5000 seconds from the initial starting point of the test. The period from 5000 seconds to the end of the experimental data collection was identified as the period of steady-state equilibrium in the network. This period is the basis of the comparison between KYPIPE simulated results and the measured experimental results. A statistical summary of the data is presented in table 9.

The trends for each data series were retroactively removed from the individual time series by adjusting the dataset based on the linear trend slope and the distance from the average value for each time series. The general methodology is described in the statistical analysis section of

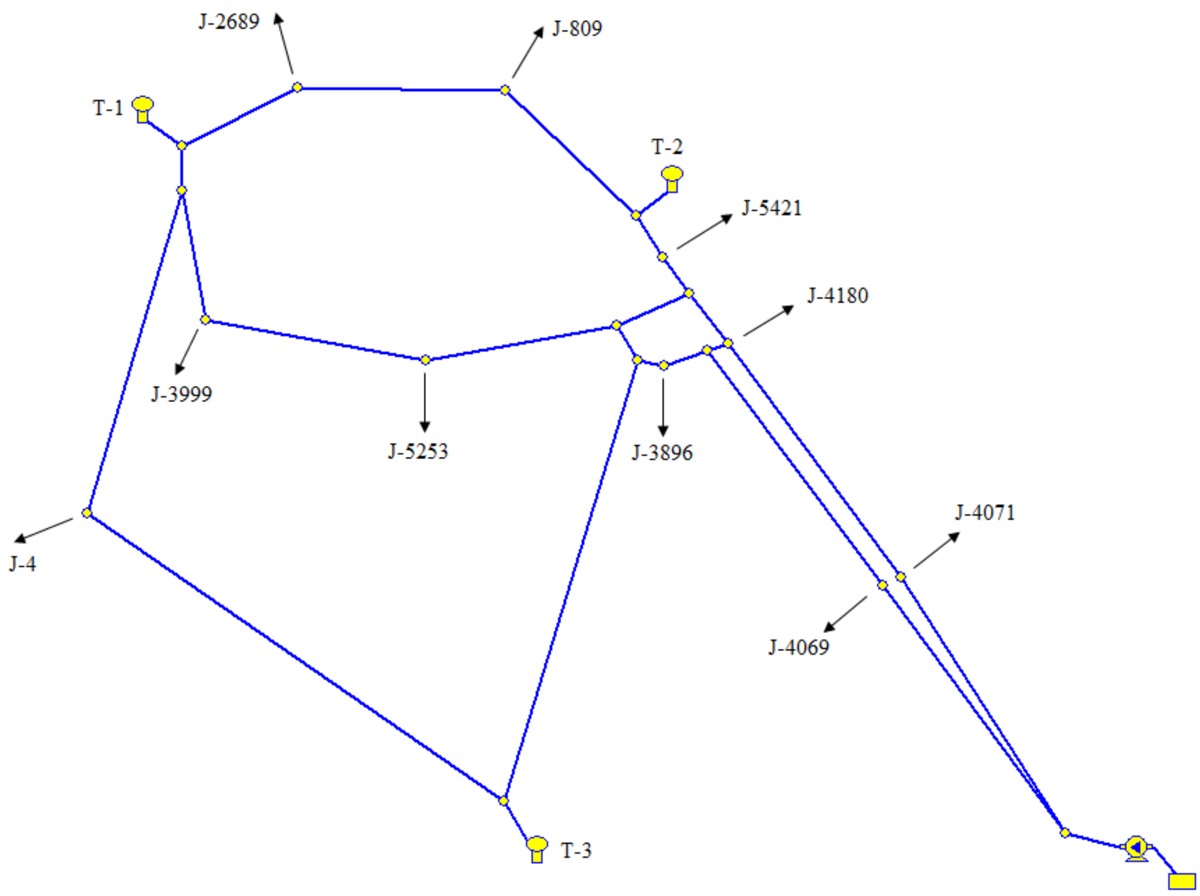

Figure 2: Steady state 1 schematic

Table 8: Steady state 1 valve settings

Valve	Number of Turns from Open
J-4	3
J-3999	4.625
J-5253	4
J-3896	1.5
J-4069	2.5
J-4071	3.75
J-4180	3.375
J-5421	4.125
J-809	4.25
J-2689	4.375

the report. Thus comparisons could then be made with other experiments without the presence of slight trends unique to each experiment. In addition, removing the trends from the dataset reduces the standard deviations of the adjusted datasets and reduces any biases in the tests for normality from mild trends in the "steady state."

Normality in the data was determined by examining the standardized residuals as described in the statistical analysis section of the report. The data for the pressure sensors, flow meters, and tank level meters were found to meet the normality criteria after removing mild trends from the time series for each instrument using the trend analysis previously described.

A check for a non-constant error variance was verified using the Szroeter test for non-constant variance. Most of the instruments error and variance in the data was not found to meet the test statistic for non-constant variance. There are some non-constant variance in the tank T-2, J-4180, and J-4071 flow meters. Many of the pressure meters had some issues with non-constant variance as well. The network was still in slight disequilibrium from steady state during data collection.

The flow rates from the experiment's mass balance had a discrepancy of about 8.89 GPM of the total flow. The flow rate data was adjusted based on meeting a flow balance throughout the network. Initially the transmission lines were increased approximately 3.9% and the outlet demands were decreased 3.9% by a constant offset to the data before creating the KYPIPE model. The KYPIPE model was used to observe the difference between the modeled pressures and measured pressures for the experiment. Another study using the physical model network showed the flow demands meters as more accurate than the transmission lines meters as described in the Steady State Hydraulics Analysis 5 section of this document. Additionally, an experimental verification made by measuring the volume of water discharged over a given length of given time found that the demand models were more accurate than the transmission lines.

A second KYPIPE model was created using the unaltered flows from the demand nodes. Table 10 presents the comparison of modeled pressures to measured pressures using both a KYPIPE model with the adjusted flows adjusted for flow balance and true demand flow measurements. The KYPIPE model was created using typical literature values of the minor and frictional loss components in the network. Again, another experiment found that the demand flow meters were more accurate to the true flow going through the network. The flow results from the transmission lines are from using a calibrated flow regression equation derived from experimental calibration.

KYPIPE Analysis for 6/4/2012 Experiment

The KYPIPE model that was developed to represent the experimental model was adjusted such that the specific demands from the experiment were added to the model. The levels from the tank meters were added as the initial tank levels within the model. The first two models varied only by the flow rates used as demands at the node; one was set for the adjusted flows in the network and another used the flow rates as measured by the demands with no adjustment. While the first two KYPIPE models were developed using the typical literature values for the frictional and minor losses, a third KYPIPE model replaced the typical literature C-factors and minor loss constants with the calibrated lumped C-factors. The performances of the three KYPIPE models are presented in Table 10.

Table 9: Steady state 1 experimental data

	Instruments	Experiment Average	Experiment Std Deviation	Std Dev/Average
Tank Levels	Right Tank (T-2)	24.8949	0.1498	0.60%
	Center Tank (T-3)	27.3795	0.1826	0.67%
	Reservoir (R-1)	48.6348	0.1443	0.30%
	Left Tank (T-1)	13.8712	0.1887	1.36%
Flow Measures Summary	Instruments	Experiment Average	Experiment Std Deviation	Std Dev/Average
	P-38 (Transmission)	59.8258	1.2667	2.12%
	P-34 (Transmission)	50.0469	1.0294	2.06%
	P-22 (T-3)	0.0000	0.1204	N/A
	P-23 (T-1)	0.0000	N/A	N/A
	J-2689	5.6379	0.1429	2.53%
	J-809	4.9681	0.1068	2.15%
	J-4180	1.7852	0.0723	4.05%
	J-3999	2.7375	0.0785	2.87%
	J-5253	6.6971	0.0935	1.40%
	J-3896	30.8988	0.3114	1.01%
	J-4071	14.4654	0.1936	1.34%
	J-4069	26.3260	0.2702	1.03%
	P-24 (T-2)	0.0000	N/A	N/A
	J-5421	6.7811	0.1015	1.50%
	J-4	18.4933	0.1999	1.08%
Pressure Summary	Instruments	Experiment Average	Experiment Std Deviation	Std Dev/Average
	J-3884	3.4247	0.0464	1.35%
	J-4090	18.1763	0.2792	1.54%
	J-5253	3.9522	0.0509	1.29%
	J-4	3.7978	0.0742	1.95%
	J-2418	3.4945	0.0488	1.40%
	J-5582	2.9160	0.0198	0.68%
	J-4180	5.5046	0.1432	2.60%
	J-809	2.9586	0.0501	1.69%
	J-2689	2.9274	0.0258	0.88%
	J-5421	3.5193	0.0612	1.74%
	J-3893	3.4038	0.0509	1.49%
	J-4186	4.1279	0.0268	0.65%
	J-3832	4.2919	0.0844	1.97%
	J-4181	4.5938	0.0878	1.91%
	J-4069	4.7704	0.1835	3.85%
	J-3999	4.4700	0.0584	1.31%
	J-3896	3.8364	0.0282	0.73%
	J-4071	6.9488	0.2576	3.71%
	J-5580	2.9890	0.0246	0.82%

Table 10: Steady state 1 measured versus modeled pressures

		Model With Demands		Model with Adj Demand Flows for Flow Balance	
Node Name	Measured Values (psi)	Modeled Values (psi)	Model To Measured Values (%)	Modeled Values (psi)	Model To Measured Values %
J-2418	3.49	3.49	99.87%	3.49	99.87%
J-2689	2.93	2.94	100.43%	2.96	101.11%
J-3832	4.29	3.96	92.27%	4.05	94.36%
J-3884	3.42	3.41	99.57%	3.52	102.78%
J-3893	3.40	3.41	100.18%	3.52	103.41%
J-3896	3.84	3.84	100.09%	3.87	100.87%
J-3999	4.47	4.30	96.20%	4.41	98.66%
J-4	3.80	3.84	101.11%	3.91	102.95%
J-4069	4.77	5.35	112.15%	5.53	115.92%
J-4071	6.95	6.88	99.01%	7.03	101.17%
J-4090	18.18	18.87	103.82%	18.97	104.37%
J-4180	5.50	5.11	92.83%	5.21	94.65%
J-4181	4.59	4.60	100.14%	4.72	102.75%
J-4186	4.13	4.15	100.54%	4.24	102.72%
J-5253	3.95	3.96	100.20%	4.05	102.47%
J-5421	3.52	3.62	102.86%	3.67	104.28%
J-5580	2.99	2.97	99.36%	2.99	100.03%
J-5582	2.92	2.97	101.85%	3.00	102.88%
J-809	2.96	2.98	100.72%	3.01	101.74%
			Average		Average
			100.17%		101.95%

Table 110 Continued: Steady state 1 measured versus modeled pressures

		Model with Demands		Model with Lumped C-factors	
Node Name	Measured Values (Psi)	Modeled Values (psi)	Model To Measured Values (%)	Modeled Pressure using Lumped C-factor (psi)	Model to Measured using Lumped C-factor (%)
J-2418	3.49	3.49	99.87%	3.48	99.58%
J-2689	2.93	2.94	100.43%	2.88	98.38%
J-3832	4.29	3.96	92.27%	3.89	90.64%
J-3884	3.42	3.41	99.57%	3.38	98.70%
J-3893	3.40	3.41	100.18%	3.38	99.30%
J-3896	3.84	3.84	100.09%	3.82	99.57%
J-3999	4.47	4.30	96.20%	4.25	95.08%
J-4	3.80	3.84	101.11%	3.82	100.58%
J-4069	4.77	5.35	112.15%	4.91	102.93%
J-4071	6.95	6.88	99.01%	7.03	101.17%
J-4090	18.18	18.87	103.82%	19.94	109.70%
J-4180	5.50	5.11	92.83%	4.97	90.29%
J-4181	4.59	4.60	100.14%	4.39	95.56%
J-4186	4.13	4.15	100.54%	4.13	100.05%
J-5253	3.95	3.96	100.20%	3.95	99.94%
J-5421	3.52	3.62	102.86%	3.57	101.44%
J-5580	2.99	2.97	99.36%	2.95	98.69%
J-5582	2.92	2.97	101.85%	2.95	101.16%
J-809	2.96	2.98	100.72%	2.91	98.36%
			Average		Average
			100.17%		99.01%

Discussion of Results for 6/4/2012 Experiment

The results of the experiment illustrated that KYPIPE and other water distribution programs matched the experimental physical data to a high average probability for this scenario. The KYPIPE model tended to over predict the pressures in the network using typical literature values and under predict slightly using the global calibrated roughness values. Utilizing the pressure meters as the basis of the water surface elevations in the tanks corrected the false inflows and outflows in the tanks and increased the accuracy between the KYPIPE model and measured values. Using the elevations as reported by water level sensors misreported the energy grade within the tanks and when running a KYPIPE analysis this error resulted in higher flows within the tank flow lines than were measured within the experiments.

The resulting pressures in table 10 were on average about 2.69% higher than indicated by the experimental results using the demand based KYPIPE model and slightly lower for the flow mass balance adjusted flow demands. Using the pressure measurements at J-5580 and J-4186 as the basis for the water surface elevation in the tank T-1 and tank T-3 reduced the discrepancy between the KYPIPE modeled pressures and the measured pressures in the network to an average of about 0.17%, as shown at the bottom of table 10. This is the average difference between modeled pressures and measured pressures for the nineteen network nodes. The model that utilized global lumped C-factors for pipe roughness performed slightly worse than the model developed with typical literature values for pipe roughness and minor losses. However both models successfully predicted, within 1.0%, the measured experimental results, on average. This is in spite of some of the disequilibrium away from steady state as indicated by the non-constant variance in the data sets as determined from Szroeter test.

Figures 3 – 6 demonstrate that from approximately 5,000 seconds from the initial start of the simulation until the end of the experiment, at 14,778 seconds, there remains some small level of disequilibrium from a truly steady state equilibrium. The tank levels were slightly adjusting during the interval by about 1.0 inches. This is also indicated in the pressure meter readings below the tanks. The graphs for the flow meters and the transmission lines during that same interval do not show any significant increase or decrease. Thus the network is still slightly away from idealized steady states during the interval of the experiment 1.4 hours until 4.1 hours from the start of the experiments.

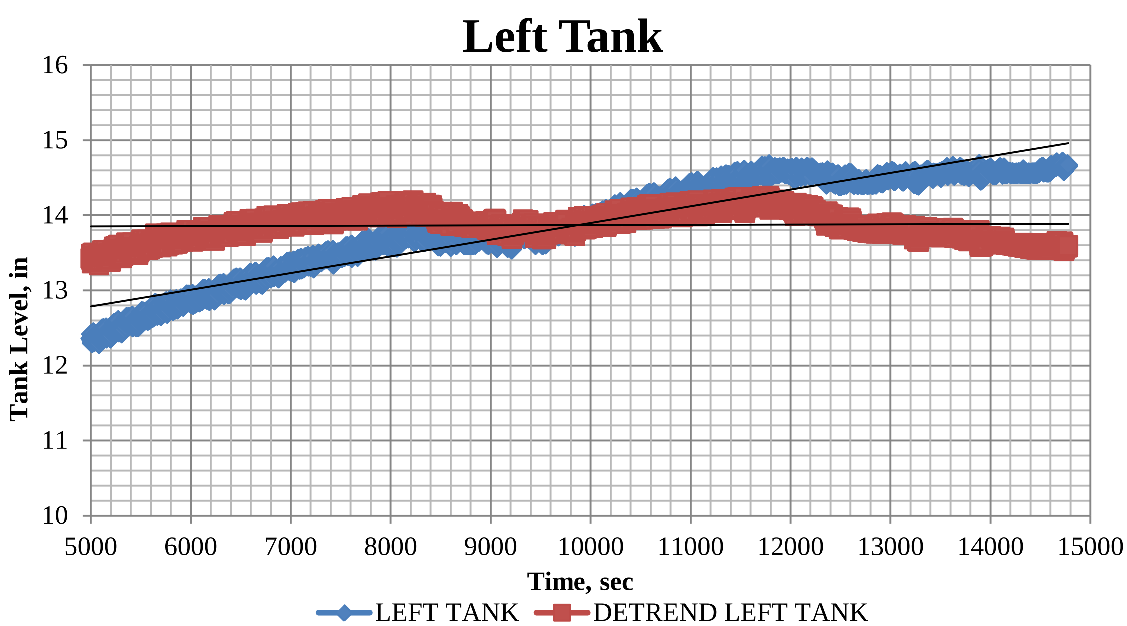

Figure 3: Steady state 1 left tank

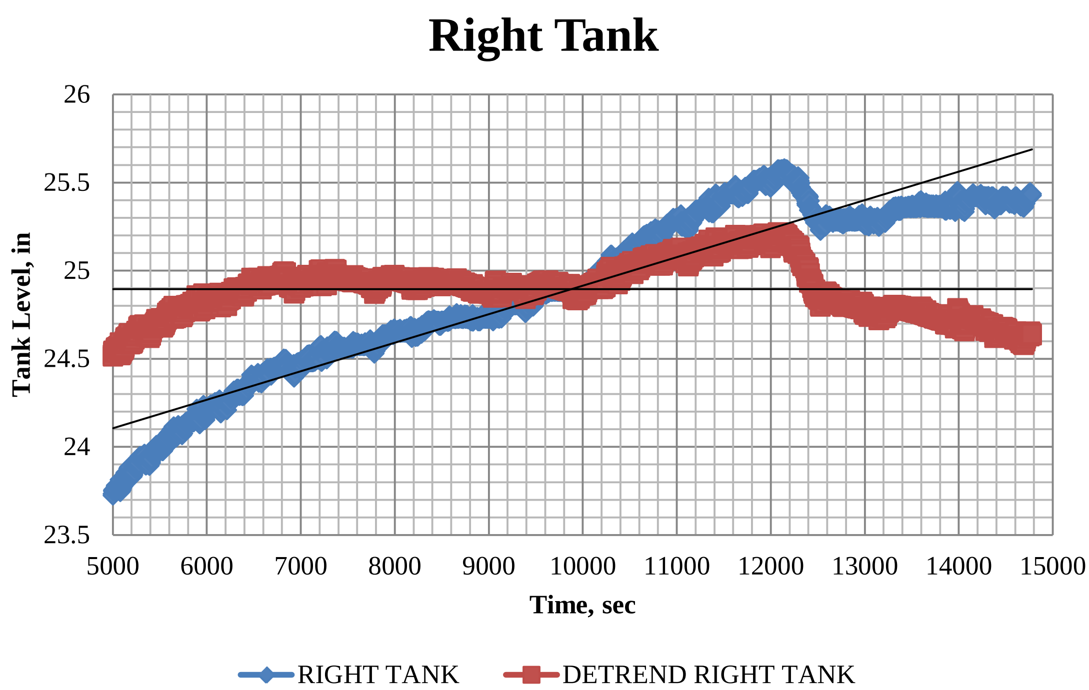

Figure 4: Steady state 1 right tank

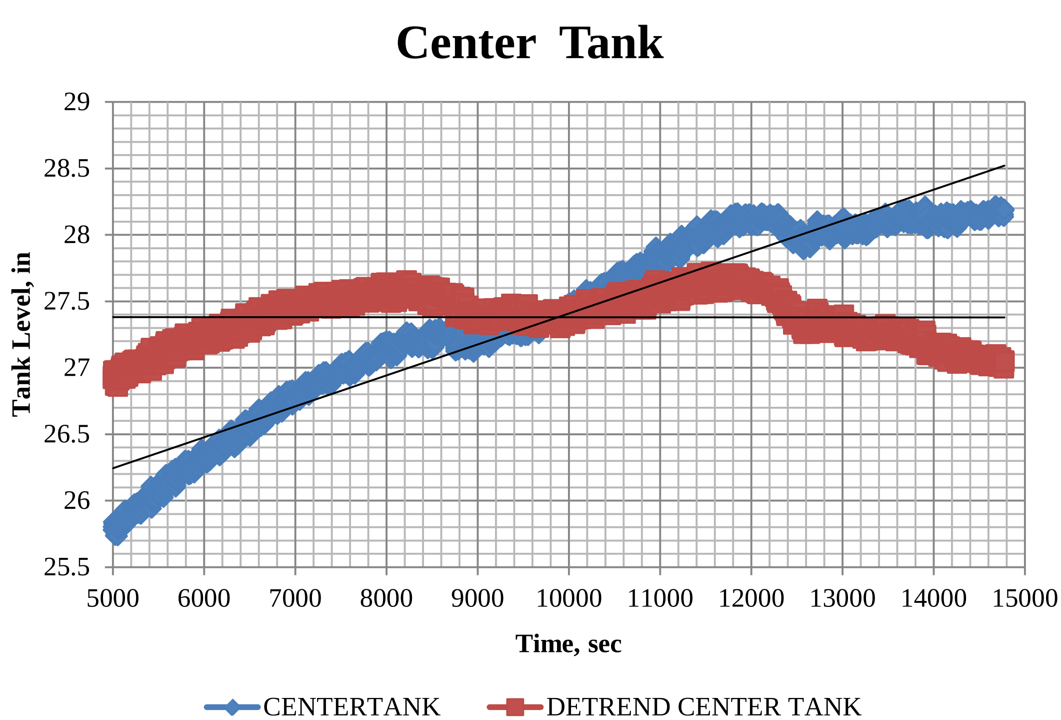

Figure 5: Steady state 1 center tank

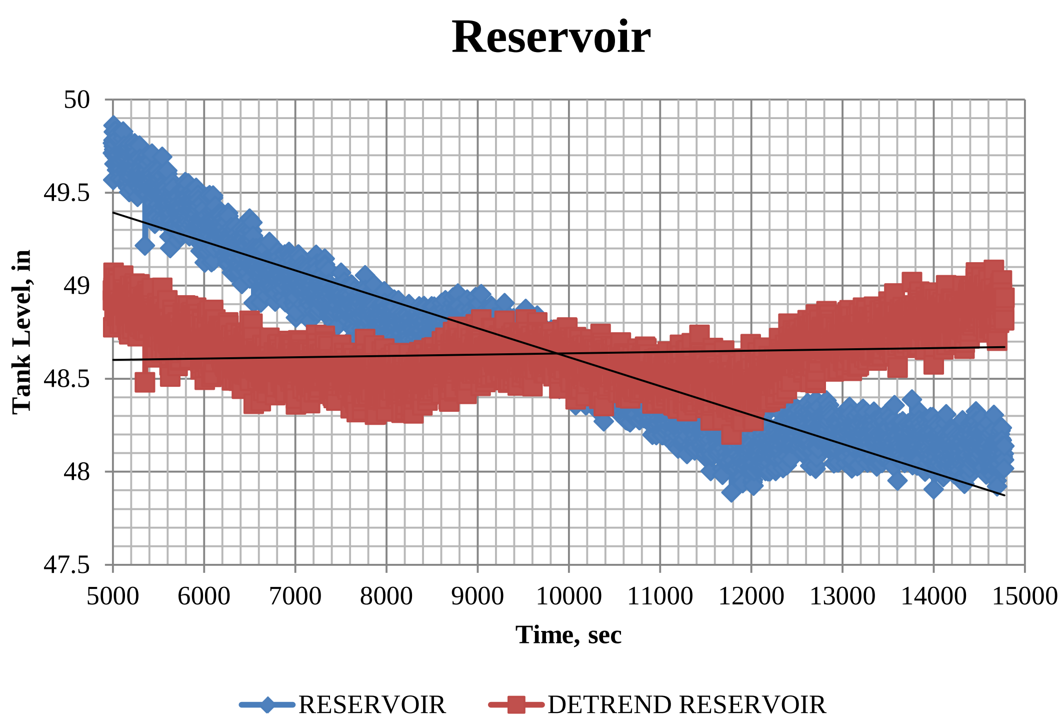

Figure 6: Steady state 1 reservoir

Steady State Hydraulics Analysis 2 (5/18)

Overview of the 5/18/2012 Experiment

The 5/18/2012 experiment was run using the standard procedure for setting up a steady state experiment. All of the pipes and tanks in the network were open, and five of the ten demand nodes were active. Prior to the test, the tanks were filled by closing off the demand valves with the pump exclusively supplying the tanks. After the tanks were full, the demand nodes were set to the settings indicated by Table 11. The pump was running throughout the procedure. The test was then run with the tanks partially full throughout the test and data acquired after some time was allowed for steady state equilibrium to be reached. The gate valves were set in an attempt to create flow throughout the remainder of the network above the minimum detectable for the flow meters. Figure 7 shows the KYPIPE schematic for this setup.

Statistical Analysis for the 5/18/2012 Experiment

A least squares regression analysis was performed for the flow meters, tank level meters, and pressure meters over the duration of the test period. This was an attempt to verify that the analysis period was at steady state equilibrium and unchanging over that interval of time. It was discovered that there tended to be a mild statistically significant trend in the dataset according to a Fisher test statistic.

The trends for each data series were removed from the individual time series by adjusting the dataset based on the linear trend slope and the distance from the average value for each time series. The methodology for performing the Fisher test as described in the statistical analysis section was followed for determining the presence or absence of a trend.

Normality in the data was determined by examining the standardized residuals. The procedure as described in the statistical analysis section of the report was followed for testing normality in the data. The flow, tank level, and pressure measurements were found to have a slope of zero according to the standardized residuals, therefore meeting the normality assumption.

A check for a non-constant error variance was verified using the Szroeter test for non-constant variance as described in the statistical analysis portion of the report. The instruments' error and variance in the data were not found to meet the test statistic for non-constant variance. The only exception was the tank level meters, however removing the trend from the data series

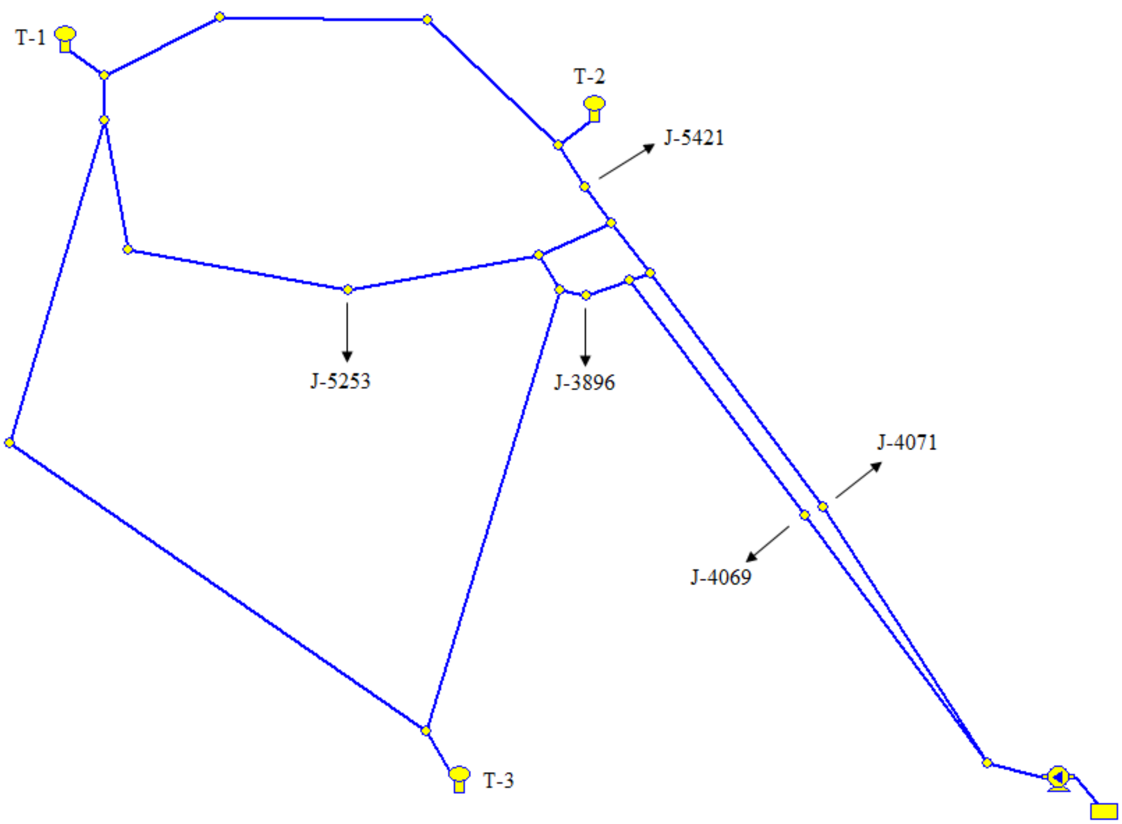

Figure 7: Steady state 2 schematic

Table 121: Steady state 2 gate valve settings

Valve	Number of Turns from Open
J-4	Closed
J-3999	Closed
J-5253	4
J-3896	0
J-4069	0
J-4071	0
J-4180	Closed
J-5421	4
J-809	Closed
J-2689	Closed

showed that without the slight trend in the tanks over time, the instruments are operating with constant variance within a steady state condition. Table 13 presents the experimental results after removing the slight trends from each time series.

The flow readings from the experiment's mass balance had a discrepancy of about 3.28 GPM between the demand flow and transmission flow readings. The flow rate data was adjusted based on meeting a flow balance throughout the network. Initially the transmission lines were reduced approximately 1.44% and the outlet demands were increased 1.44% by a constant offset to the data before creating the KYPIPE model. The KYPIPE model would be used to observe the difference between the modeled pressures and measured pressures for the experiment. Another study using the physical model network showed the flow demands meters as more accurate than the transmission lines meters. Additionally, an experimental verification made by measuring the volume of water discharged over a given interval of time found that the demand models were more accurate than the transmission lines. Another KYPIPE model was created using the unaltered flow measurements at the demand nodes. Table 13 presents the comparison of modeled pressures to measured pressures using both a KYPIPE model with the adjusted flows adjusted for flow balance and true demand flow measurements.

The first two KYPIPE models were created using typical literature values of the minor loss components in the network. The comparison between the modeled to measured pressure results for both the flow adjusted model (to meet flow balance) and flow model created using the demand flow measurements and presented in table 13. Again, another experiment found that the demand flow meters were more accurate to the true flow going through the network. The flow results from the transmission lines are from using a calibrated flow regression equation derived from experimental calibration.

The third KYPIPE model replaced the typical minor losses values and pipe roughness values with calibrated lumped parameter pipe roughness values and excluded minor loss coefficients in the network. The performances of the three KYPIPE models are presented in table 13.

KYPIPE Analysis of the 5/18/2012 Experiment

The KYPIPE model developed for the experimental model was adjusted such that the specific demands from the experiment were added to the model. The levels from the tank meters were added as the initial tank levels within the model. The first two models varied only by the flow rates used as demands at the node; one used the adjusted flows in the network and the other used the flow rates as measured by the demands with no adjustment. While the first two KYPIPE models were developed using the typical literature values for the frictional and minor losses, a third KYPIPE model replaced the typical literature C-factors and minor loss constants with the calibrated lumped C-factors. Table 13 summarizes the resulting pressures from the three models.

Discussion of the 5/18/2012 Experiment

The results of the experiment illustrated that KYPIPE and other water distribution programs matched the experimental physical data to a high average probability for this scenario. As shown in Table 13, the resulting pressures for the nineteen nodes were on average about 1.75% higher than indicated by the experimental results for the demand-based flow KYPIPE model and 2.16% higher for the flow mass balance adjusted flow demands. The model that utilized the lumped C-factor approach performed the best with resulting pressures deviating from the data by an average of 1.07%. Overall, the KYPIPE model tended to underpredict the pressures in the network. This most likely represents slightly deviations from literature values for the various K factors and C-factors for the pipes in the network.

Table 132: Steady state 2 experimental data

	Instrument	Experiment Average (inches)	Experiment Std Deviation	Std Dev/Average
Tank	Right Tank (T-2)	26.10413459	0.076319348	**0.29%**
	Center Tank (T-3)	25.34135927	0.111294138	**0.44%**
	Reservoir (R-1)	24.30485006	0.156364346	**0.64%**
	Left Tank (T-1)	25.72250695	0.095047902	**0.37%**
Flow Measures Summary	**Instrument**	**Experiment Average (GPM)**	**Experiment Std Deviation**	**Std Dev/Average**
	P-38 (Transmission)	58.45813324	1.216226645	**2.08%**
	P-34 (Transmission)	55.17938069	1.18204859	**2.14%**
	P-22 (T-3)	0	0.083463703	**N/A**
	P-23 (T-1)	0	0.039742051	**N/A**
	J-2689	0	0.037980815	**N/A**
	J-809	0	0.038044015	**N/A**
	J-4180	0	0.039870233	**N/A**
	J-3999	0	0.044632634	**N/A**
	J-5253	1.544337572	0.081868784	**5.30%**
	J-3896	32.80467838	0.344297066	**1.05%**
	J-4071	36.50129555	0.394942811	**1.08%**
	J-4069	34.38496904	0.35366139	**1.03%**
	P-24 (T-2)	0	0.037999782	**N/A**
	J-5421	8.402233388	0.105831539	**1.26%**
	J-4	0	0.043686615	**N/A**
Pressure Summary	**Instrument**	**Experiment Average (psi)**	**Experiment Std Deviation**	**Std Dev/Average**
	J-3884	3.524565542	0.082977937	**2.35%**
	J-4090	16.84186842	0.323249105	**1.92%**
	J-5253	4.420494559	0.056705084	**1.28%**
	J-4	4.331003481	0.026922838	**0.62%**
	J-2418	3.584244605	0.048695089	**1.36%**
	J-5582	3.479418762	0.025344436	**0.73%**
	J-4180	4.717189846	0.185422804	**3.93%**
	J-809	3.510551225	0.057793853	**1.65%**
	J-2689	3.471935415	0.047562437	**1.37%**
	J-5421	3.490229369	0.095712273	**2.74%**
	J-3893	3.478673797	0.078391278	**2.25%**
	J-4186	4.340447139	0.03160756	**0.73%**
	J-3832	3.760167778	0.137665597	**3.66%**
	J-4181	4.478285496	0.088325881	**1.97%**
	J-4069	4.055360517	0.179714944	**4.43%**
	J-3999	4.359994571	0.077407102	**1.78%**
	J-3896	4.381051841	0.013062015	**0.30%**
	J-4071	4.32729913	0.182340577	**4.21%**
	J-5580	3.530393443	0.028736801	**0.81%**

Table 143: Steady state 2 measured versus modeled pressures

	Model with Demands		Model with Adj Demand Flows for Flow Balance	
Measured Values (psi)	**Model Values (psi)**	**Model to Measured (%)**	**Model Values (psi)**	**Model to Measured (%)**
3.58	3.54	**98.77%**	3.54	**98.77%**
3.47	3.54	**101.96%**	3.54	**101.96%**
3.76	3.7	**98.40%**	3.72	**98.93%**
3.52	3.55	**100.72%**	3.58	**101.57%**
3.48	3.55	**102.05%**	3.58	**102.91%**
4.38	4.42	**100.89%**	4.44	**101.35%**
4.36	4.4	**100.92%**	4.41	**101.15%**
4.33	4.42	**102.05%**	4.44	**102.52%**
4.06	4.51	**111.21%**	4.56	**112.44%**
4.33	4.57	**105.61%**	4.62	**106.76%**
16.84	17.56	**104.26%**	17.59	**104.44%**
4.72	4.67	**99.00%**	4.69	**99.42%**
4.48	4.55	**101.60%**	4.57	**102.05%**
4.34	4.42	**101.83%**	4.44	**102.29%**
4.42	4.41	**99.76%**	4.42	**99.99%**
3.49	3.54	**101.43%**	3.54	**101.43%**
3.53	3.54	**100.27%**	3.54	**100.27%**
3.48	3.54	**101.74%**	3.55	**102.03%**
3.51	3.54	**100.84%**	3.54	**100.84%**
		Average		**Average**
		101.75%		102.16%

Table 153 Continued: Steady state 2 measured versus modeled pressures

	Model with Demands		Model with Demand Flows using Global C-factor	
Measured Values (Psi)	**Model Values**	**% Model To Measured**	**Model Values**	**% Model To Measured**
3.58	3.54	**98.77%**	3.53	**98.49%**
3.47	3.54	**101.96%**	3.53	**101.67%**
3.76	3.7	**98.40%**	3.65	**97.07%**
3.52	3.55	**100.72%**	3.52	**99.87%**
3.48	3.55	**102.05%**	3.52	**101.19%**
4.38	4.42	**100.89%**	4.38	**99.98%**
4.36	4.4	**100.92%**	4.39	**100.69%**
4.33	4.42	**102.05%**	4.38	**101.13%**
4.06	4.51	**111.21%**	4.27	**105.29%**
4.33	4.57	**105.61%**	4.55	**105.15%**
16.84	17.56	**104.26%**	18.58	**110.32%**
4.72	4.67	**99.00%**	4.6	**97.52%**
4.48	4.55	**101.60%**	4.44	**99.15%**
4.34	4.42	**101.83%**	4.38	**100.91%**
4.42	4.41	**99.76%**	4.38	**99.08%**
3.49	3.54	**101.43%**	3.52	**100.85%**
3.53	3.54	**100.27%**	3.53	**99.99%**
3.48	3.54	**101.74%**	3.53	**101.45%**
3.51	3.54	**100.84%**	3.53	**100.55%**
		Average		**Average**
		101.75%		101.07%

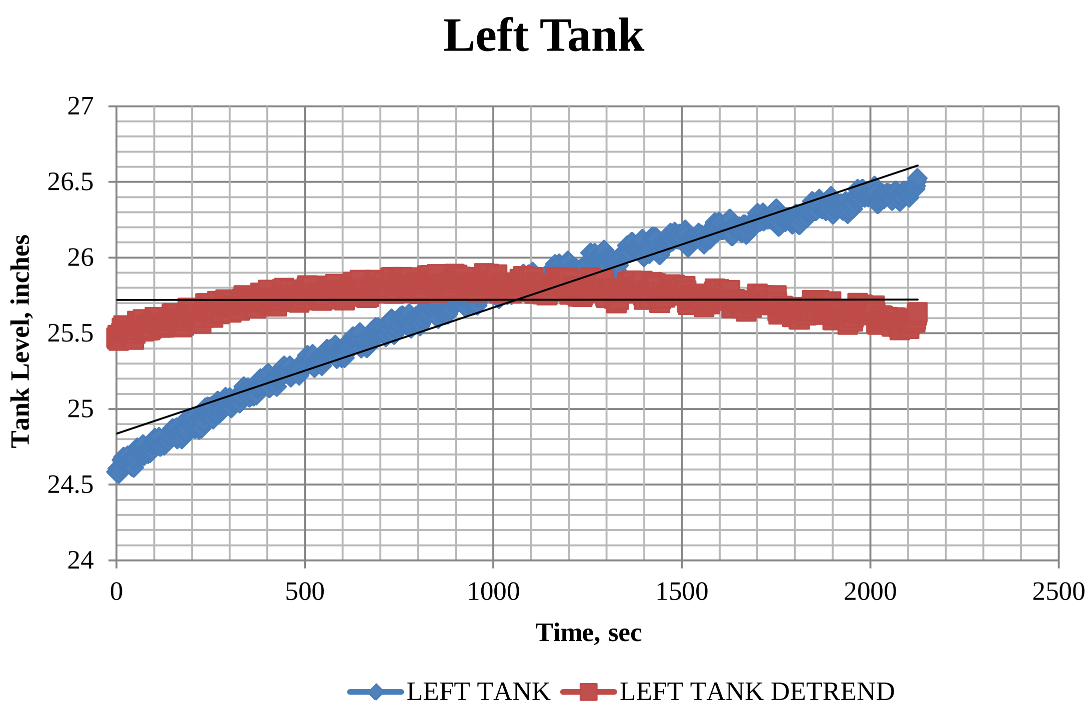

Figure 8: Steady state 2 left tank

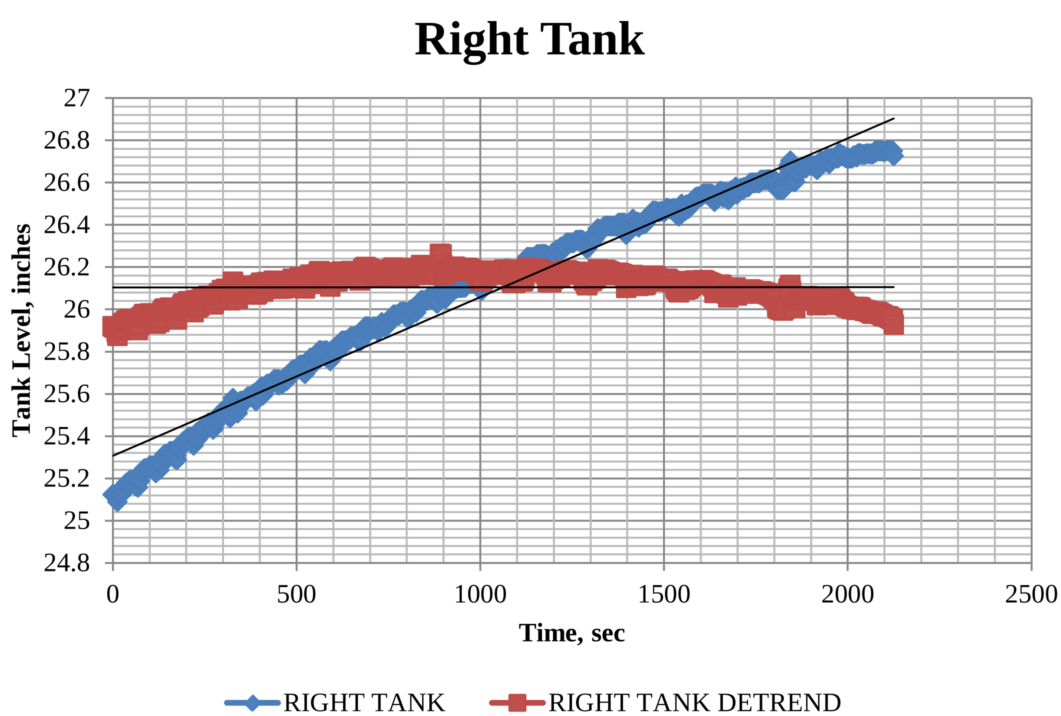

Figure 9: Steady state 2 right tank

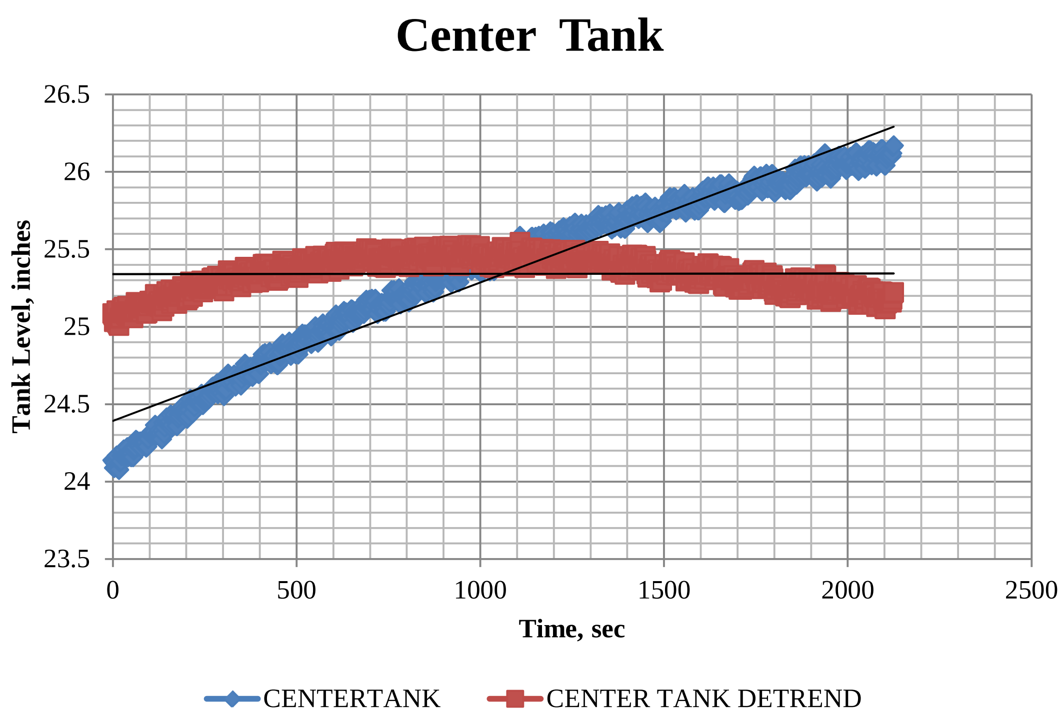

Figure 10: Steady state 2 center tank

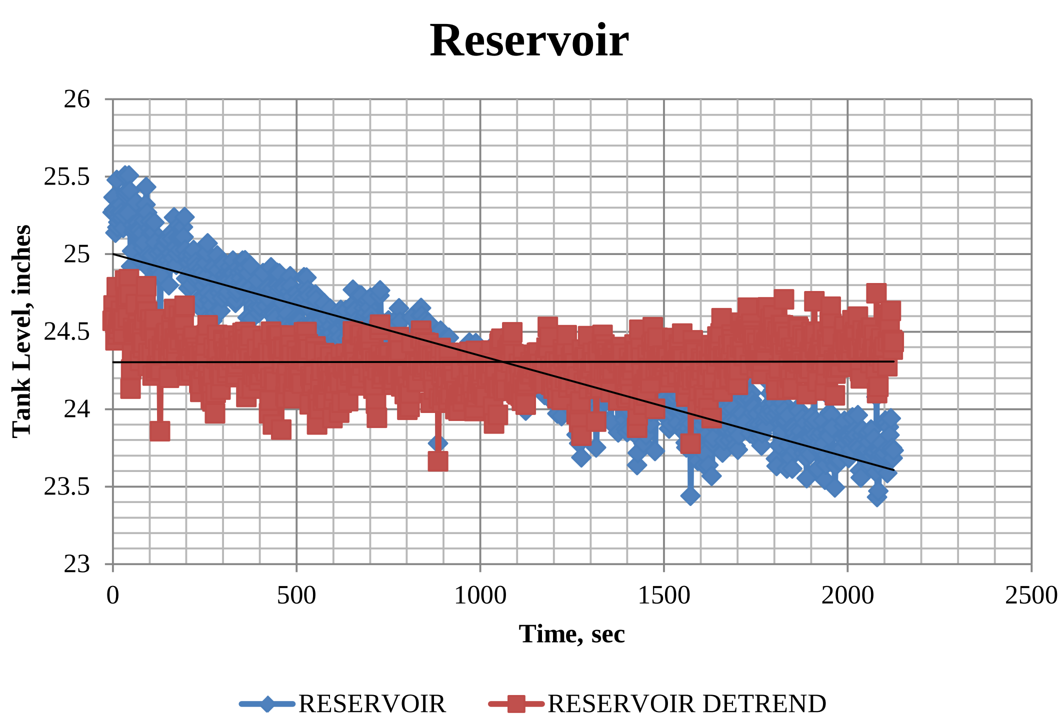

Figure 11: Steady state 2 reservoir

Steady State Hydraulics Analysis 3 (6/1)

Overview of the 6/1/2012 Experiment

The experiment was set up following the standard procedure for setting up a steady state experiment. Prior to the test, the tanks were filled by closing off each of the demand nodes with the pump running and exclusively supplying the tank flow lines. After the tanks were sufficiently filled, the gate valves were adjusted to the settings as described in table 14. The pump was on throughout the duration of the procedure. The gate valves were partially closed such that the pressure of the system was enough to keep the tanks partially filled in equilibrium. The test network was allowed to run for several hours in order to equalize to the steady state condition. Figure 12 shows a KYPIPE schematic for this setup.

Statistical Analysis of the 6/1/2012 Experiment

A least squares regression analysis was performed for the test period. This was done for the flow meters, tank level meters, and pressure meters datasets in an attempt to verify that the analysis period was at steady state equilibrium and unchanging over each interval of time. It was discovered that there tended to be a mild statistically significant trend in the dataset according to a Fisher test statistic.

The trends for each data series were removed from the individual time series by adjusting the dataset based on the linear trend slope and the distance from the average value for each time series. The basis for determining the presence of trend was the Fisher test as described in the statistical analysis section of the report. Normality in the data was determined using the methodology discussed in statistical analysis section of the report. This was found true for the de-trended flow, tank level, and pressure measurements and thus the data meets the normality assumption for both time periods.

A check for a non-constant error variance was verified using the Szroeter test for non-constant variance. The instrument's error and variance in the data was not found to meet the test statistic for non-constant variance. Thus the assumption of constant variance couldn't be disproved using the Szroeter test statistic and so the variance can be safely assumed to be constant or near constant by the Szroeter test. This was the case for all instruments. Table 15 presents the work of the experiment after removing the slight trends from each time series.

The flow rates from the experiment's mass balance had a discrepancy of about 6.45 GPM between the demand flow meters and the transmission line flow meters for the test. The demand nodes showed higher flow than the sum of the transmission lines. The flow rate data was adjusted based on meeting a flow balance throughout the network. Initially the modeled flow of the transmission lines was increased by approximately 2.90% and the outlet demands were decreased 2.90% by a constant offset to the data before creating the KYPIPE model. The flow results from the transmission lines are from using a calibrated flow regression equation derived from the experimental calibration. The KYPIPE model was used to observe the difference between the modeled pressures and measured pressures for the experiment. Table 16 presents the comparison of modeled pressures to measured pressures using both a KYPIPE model with the adjusted flows adjusted for flow balance and true demand flow measurements. Using the demand nodes showed the highest correlation between modeled and measured pressures at the nodes in the network.

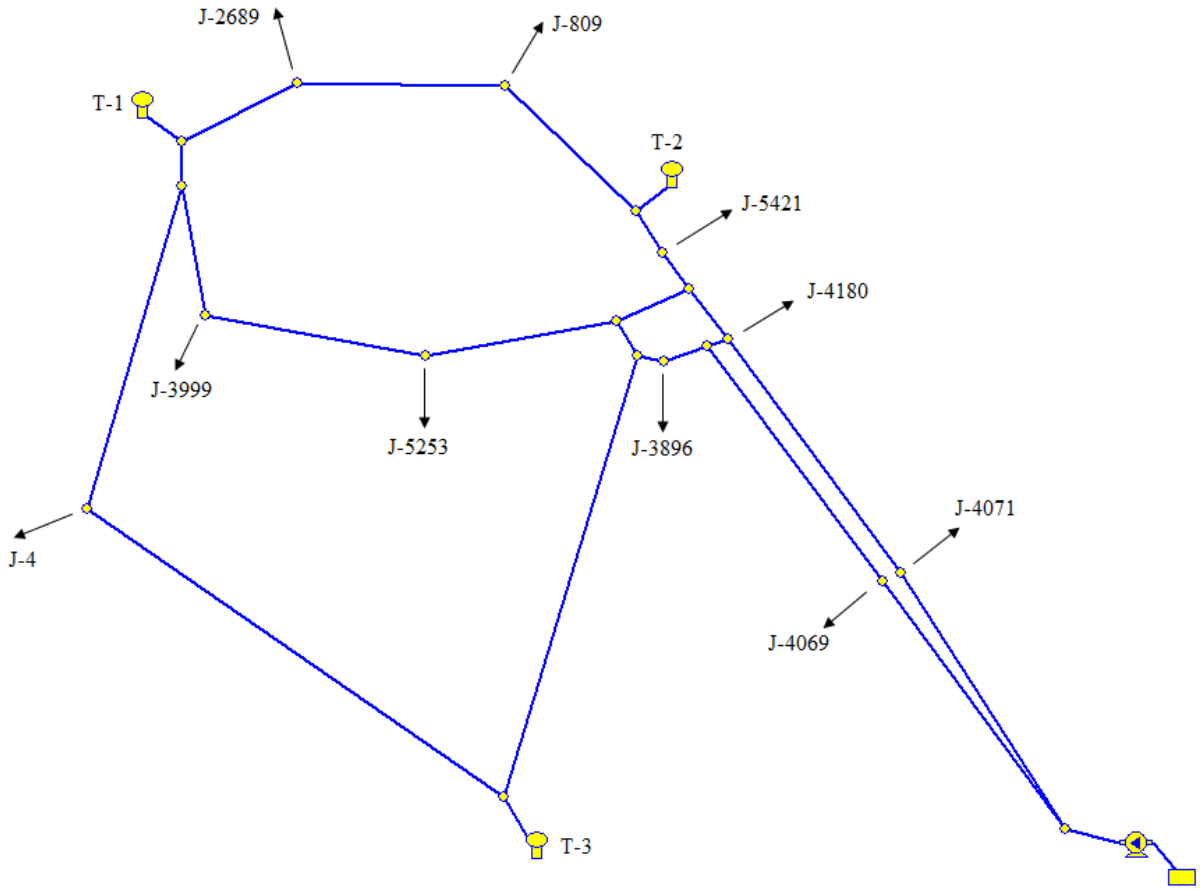

Figure 12: Steady state 3 schematic

Table 164: Steady state 3 gate valve settings

Valve	Number of Turns from Open
J-4	3
J-3999	4.75
J-5253	4
J-3896	1.5
J-4069	2.5
J-4071	3.75
J-4180	3.75
J-5421	4.125
J-809	4.5
J-2689	4.25

Table 175: Steady state 3 experimental data

Section	Instrument	Experiment Average (inches)	Experiment Std Deviation	Std Dev/Average
Tank Level	**Right Tank (T-2)**	21.04121971	0.022102474	**0.11%**
	Center Tank (T-3)	24.98711402	0.019499233	**0.08%**
	Reservoir (R-1)	26.11568662	0.077196899	**0.30%**
	Left Tank (T-1)	10.81774816	0.028639572	**0.26%**
Flow Measures Summary	**Instrument**	**Adjusted Averages (gpm)**	**Experiment Std Deviation**	**Std Dev/Average**
	P-38 (Transmission)	60.93026598	1.196203294	**1.96%**
	P-34 (Transmission)	50.91197921	1.066855714	**2.10%**
	P-22 (T-3)	0	0.098554368	**N/A**
	P-23 (T-1)	0	0.047799803	**N/A**
	J-2689	5.121458324	0.084811307	**1.66%**
	J-809	3.060373497	0.073589427	**2.40%**
	J-4180	0	0.199050006	**N/A**
	J-3999	2.137920263	0.060155369	**2.81%**
	J-5253	6.381846869	0.096030281	**1.50%**
	J-3896	29.95491884	0.284928061	**0.95%**
	J-4071	14.16949295	0.240683039	**1.70%**
	J-4069	25.07604851	0.262636352	**1.05%**
	P-24 (T-2)	0	0.036961306	**N/A**
	J-5421	6.520350974	0.080333987	**1.23%**
	J-4	19.41983497	0.00039459	**0.00%**
Pressure Summary	**Instrument**	**Experiment Average (psi)**	**Experiment Std Deviation**	**Std Dev/Average**
	J-3884	3.321465564	0.062906662	**1.89%**
	J-4090	17.84960605	0.240199797	**1.35%**
	J-5253	3.847272873	0.045129051	**1.17%**
	J-4	3.692501527	0.073302438	**1.99%**
	J-2418	3.415228909	0.029190879	**0.85%**
	J-5582	2.838589345	0.025918099	**0.91%**
	J-4180	5.316763891	0.148014522	**2.78%**
	J-809	2.903206273	0.038983699	**1.34%**
	J-2689	2.8125852	0.050077509	**1.78%**
	J-5421	3.433285527	0.059764852	**1.74%**
	J-3893	3.296876927	0.057662308	**1.75%**
	J-4186	4.013114309	0.042623933	**1.06%**
	J-3832	4.152484018	0.096597497	**2.33%**
	J-4181	4.456994927	0.092644967	**2.08%**
	J-4069	4.617798527	0.178962893	**3.88%**
	J-3999	4.358652909	0.067202925	**1.54%**
	J-3896	3.751495055	0.025831333	**0.69%**
	J-4071	6.7554382	0.233358625	**3.45%**
	J-5580	2.8993382	0.033271727	**1.15%**

KYPIPE Analysis for 6/1/2012 Experiment

The KYPIPE models were developed for the experimental model and were adjusted such that the specific demands from the experiment were added to the models. The levels from the tank meters were added as the initial tank levels within the model. One model was run using the flow rates adjusted for flow balance and using typical literature values for minor losses and pipe roughness in the network. A second model run using the flow as measured by the demands with no adjustment and using typical literature values for the minor loses and pipe roughness in the network. A third KYPIPE model was developed using the unaltered demand flows and with calibrated pipe roughness values. The performances of the three KYPIPE models are presented in table 16. It was found that using the pressure head from the J-4186 pressure meter plus the elevation at the J-4186 directly below Tank 3 disagreed significantly with the tank meter average measured value. The difference was between 18.26 feet based on the pressure meter and 19.08 feet based on the tank meter. Using the value recorded from the pressure meter reduced the discrepancy between modeled to measured pressures to within 1% as indicated in table 16. The other tank pressure meters matched the recorded measurement for the tank level meter.

Discussion of 6/1/2012 Experiment

The results of the experiment illustrated that KYPIPE and other water distribution programs matched the experimental physical data to a high average probability for this scenario. The results were on average about 0.83% higher than an indicated by the experimental results for the demand based flow KYPIPE model and 1.36% higher for the flow mass balance adjusted flow demands model. The model that utilized the calibrated C-factors performed the best, under predicting the pressures by an average of 0.15%. Figures 13 – 16 show the tank levels over time.

Table 186: Steady state 3 modeled versus measured pressure

Node Name	Measured Pressure (psi)	Modeled Pressure using Adjusted demands (psi)	% Diff using Adjusted Demands	Modeled Pressure using Demand Data (psi)	% Diff using Demand Data	Modeled Pressure using Lumped C-factor (psi)	% Diff using Lumped C-factor
J-2418	3.42	3.36	**98.38%**	3.36	**98.38%**	3.36	**98.38%**
J-2689	2.81	2.94	**104.53%**	2.95	**104.89%**	2.9	**103.11%**
J-3832	4.15	3.86	**92.96%**	3.89	**93.68%**	3.81	**91.75%**
J-3884	3.32	3.29	**99.05%**	3.31	**99.65%**	3.27	**98.45%**
J-3893	3.30	3.29	**99.79%**	3.31	**100.40%**	3.27	**99.18%**
J-3896	3.75	3.82	**101.83%**	3.83	**102.09%**	3.8	**101.29%**
J-3999	4.36	4.18	**95.90%**	4.21	**96.59%**	4.15	**95.21%**
J-4	3.69	3.75	**101.56%**	3.76	**101.83%**	3.71	**100.47%**
J-4069	4.62	5.19	**112.39%**	5.27	**114.12%**	4.77	**103.30%**
J-4071	6.76	6.67	**98.74%**	6.74	**99.77%**	6.81	**100.81%**
J-4090	17.85	18.45	**103.36%**	18.5	**103.64%**	19.41	**108.74%**
J-4180	5.32	5.02	**94.42%**	5.05	**94.98%**	4.89	**91.97%**
J-4181	4.46	4.48	**100.52%**	4.52	**101.41%**	4.29	**96.25%**
J-4186	4.01	4.01	**99.92%**	4.01	**99.92%**	4.01	**99.92%**
J-5253	3.85	3.89	**101.11%**	3.92	**101.89%**	3.88	**100.85%**
J-5421	3.43	3.5	**101.94%**	3.52	**102.53%**	3.46	**100.78%**
J-5580	2.90	2.96	**102.09%**	2.96	**102.09%**	2.94	**101.40%**
J-5582	2.84	2.95	**103.92%**	2.96	**104.28%**	2.94	**103.57%**
J-809	2.90	3	**103.33%**	3.01	**103.68%**	2.95	**101.61%**
			Average Difference		**Average Difference**		**Average Difference**
			100.83%		**101.36%**		**99.85%**

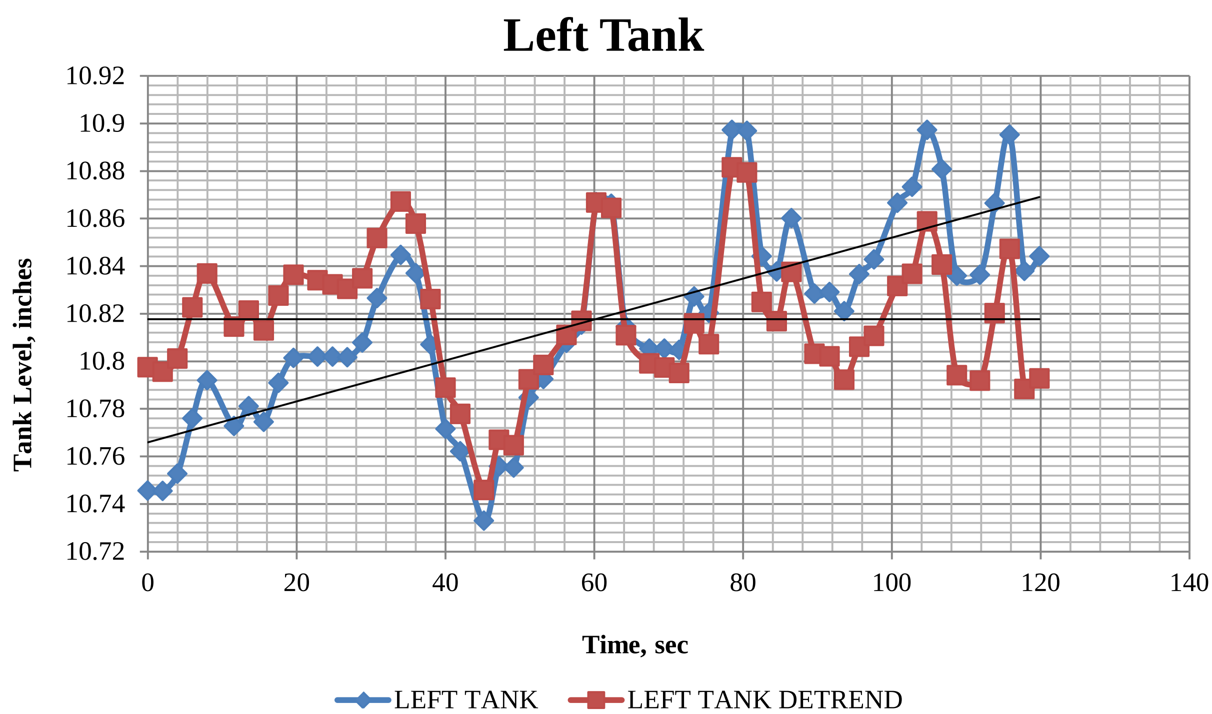

Figure 13: Steady state 3 left tank

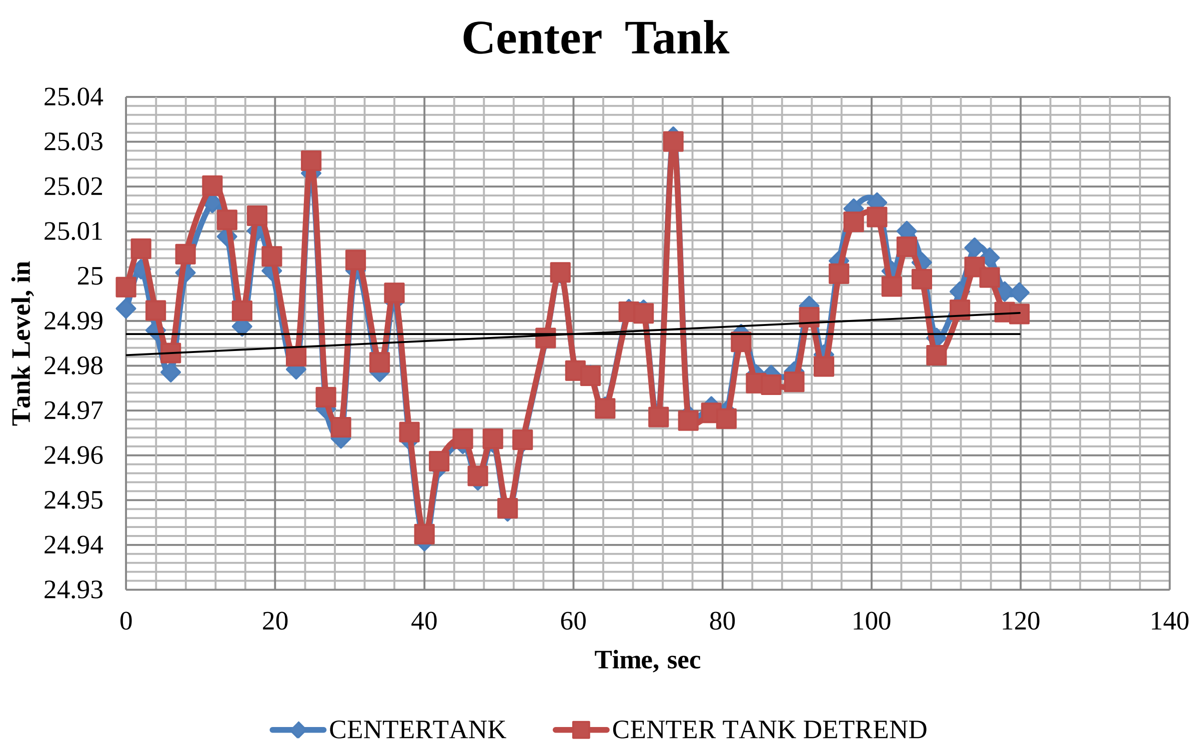

Figure 14: Steady state 3 center tank

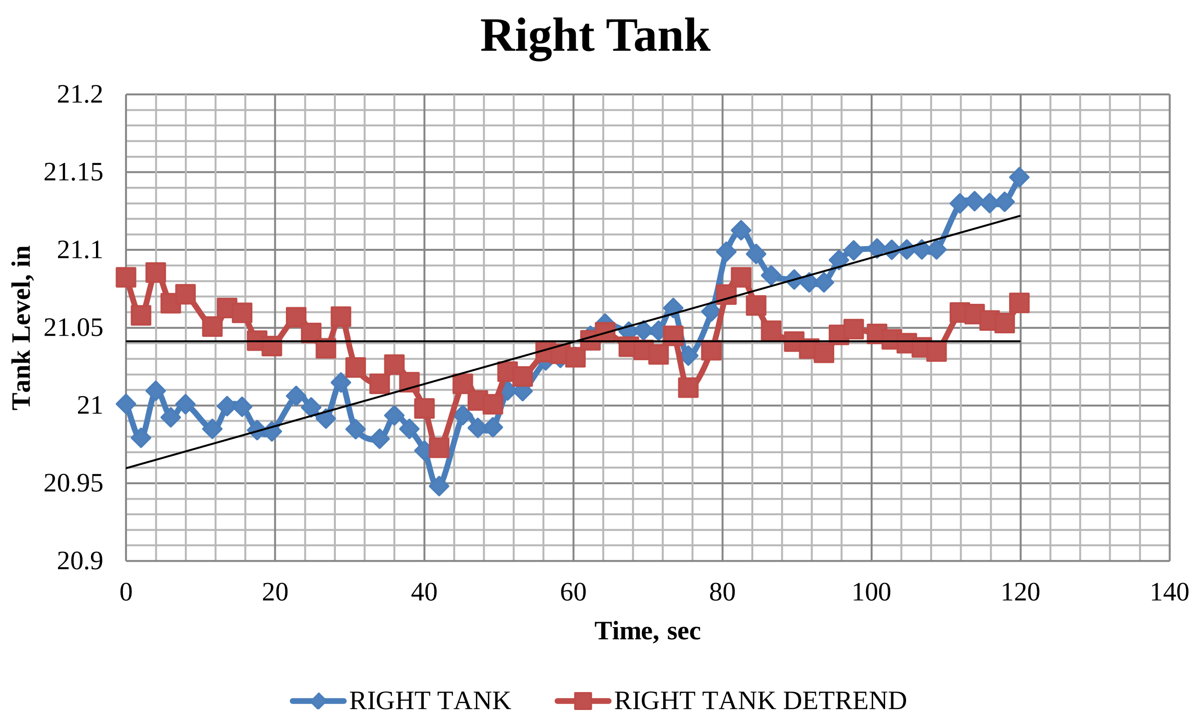

Figure 15: Steady state 3 right tank

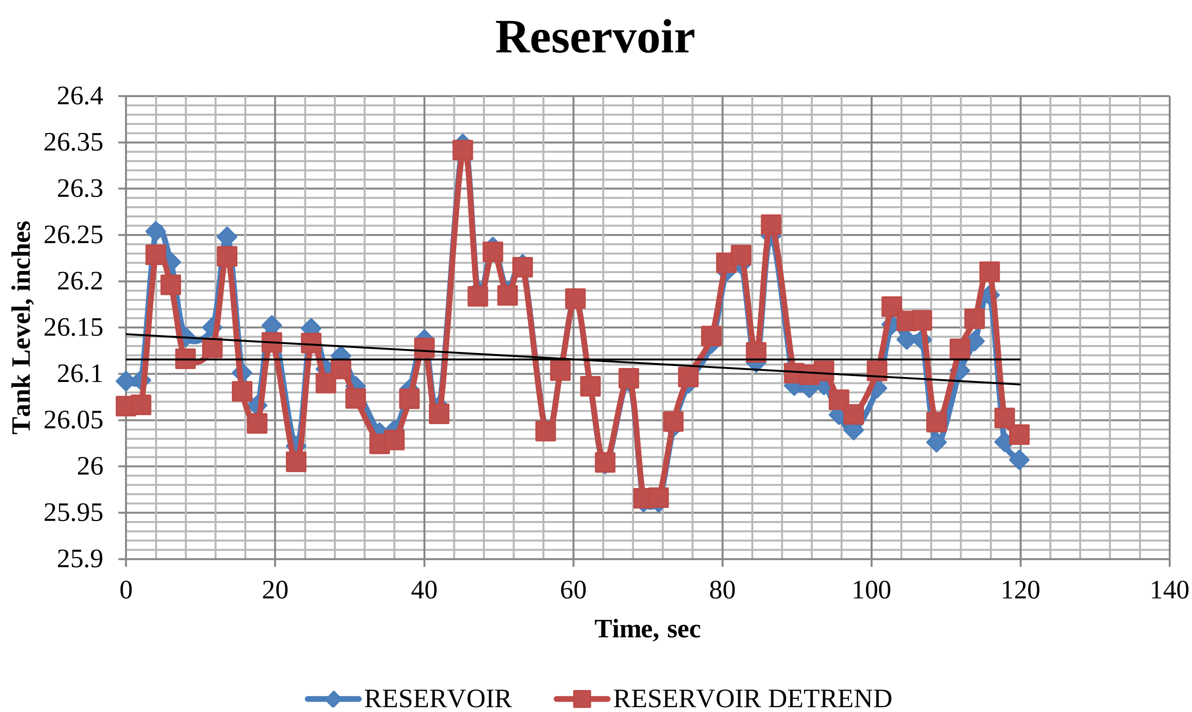

Figure 16: Steady state 3 reservoir

Steady State Hydraulics Analysis 4 (6/20)

Overview of the 6/20/2012 Experiment

The general procedure for setting up the experiment was that used in other tests. The tanks were filled prior to the steady state simulation by closing off the demand valves with the pump exclusively supplying the tanks. The tank gate valves were fully open to allow them to fill up to approximately ¾ of the fill height within the tanks. After the tanks were full, the demand nodes were set according to table 17. The pump was running throughout the procedure. The network was allowed to equalize over the course of a few hours and reach a fully steady state equilibrium.

Figure 17 is a schematic of the network showing the pipelines that were closed within the experiment. In this particular experiment, pipes P-28, P-7, P-3 and P-5 were closed off to create a branched system configuration. As illustrated in figure 17, this creates a network configuration with limited pathways for water and contaminants in flow within the network. The purpose of the experiment was to investigate the hydraulic behavior of the physical model experimental results with the modeled results for a branched flow system.

Statistical Analysis of the 6/20/2012 Experiment

A least squares regression analysis was performed for the test period and for the flow meters, tank level meters, and pressure meters datasets. This was an attempt to verify that the analysis period was at steady state equilibrium and unchanging over that interval of time. It was discovered that there tended to be a mild statistically significant trend in the dataset according to a Fisher test statistic.

The trend for each data series was removed from the individual time series by adjusting the dataset based on the linear trend slope and the distance from the average value for each time series. The methodology for trend analysis using the Fisher test presented in the statistical analysis section of report was followed in experiment.

Normality in the data was determined by examining the standardized residuals, which are the measured data points minus the regression predicted data points as a function of time and then divided by the standard deviation of the dataset. The methodology for testing normality in the data is described in the statistical analysis section of the report. This was found be true for the de-trended flow, tank level, and pressure measurements and thus the data meets the normality assumption.

A check for a non-constant error variance was verified using the Szroeter test for non-constant variance. The instrument’s data series were all not found to meet the Szroeter for non-constant variance. Thus the constant variance assumption couldn’t be rejected for the data series.

The flow rates from the experiment’s mass balance had a discrepancy of about 10.88 GPM of the total flow. The flow rate data was adjusted based on meeting a flow balance throughout the network. Initially the transmission lines were increased approximately by about 5.3 GPM and the outlet demands were decreased by about 5.4 GPM using a least squares regression to create a constant offset to the data before creating the KYPIPE model. The KYPIPE model was then used to measure the difference between the modeled pressures and measured pressures for the experiment. Table 18 presents a summary of the statistics for the data collected during the experiment.

A second KYPIPE model was created using the unaltered flows from the demand nodes. Table 19 presents the comparison of modeled pressures to measured pressures using both a

Table 197: Steady state 4 gate valve settings

Valve	Number of Turns from Open
J-4	0
J-3999	4.5
J-5253	4.5
J-3896	4.25
J-4069	3.88
J-4071	4.5
J-4180	4.25
J-5421	4.0
J-809	3.5
J-2689	0

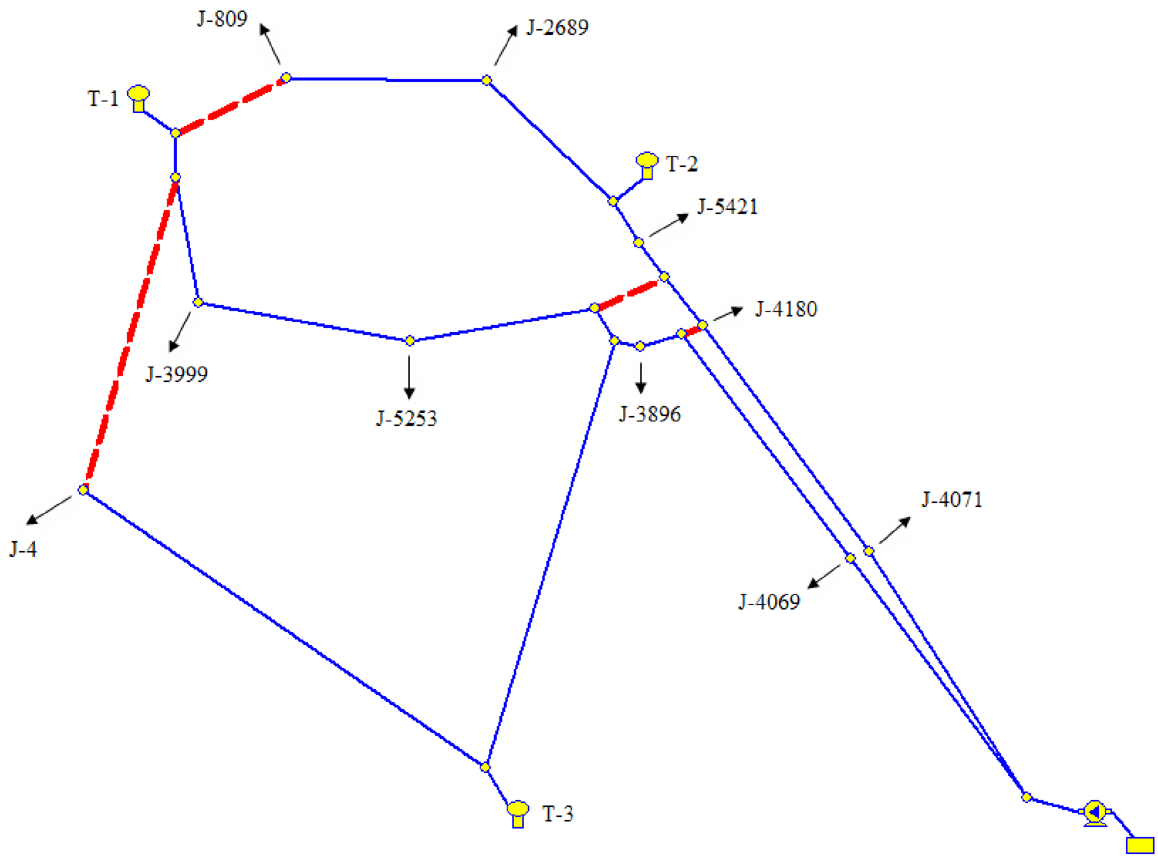

Figure 17: Steady state 4 schematic

Table 1820: Steady state 4 experimental data

	Instruments	Experiment Average	Experiment Std Deviation	Std Dev/Average
Tank	Right Tank (T-2)	23.6595	0.0107	**0.05%**
	Center Tank (T-3)	28.7750	0.0394	**0.14%**
	Reservoir (R-1)	23.6796	0.0954	**0.40%**
	Left Tank (T-1)	18.7801	0.0400	**0.21%**
Flow Measures Summary	**Instruments**	**Experiment Average**	**Experiment Std Deviation**	**Std Dev/Average**
	P-38 (Transmission)	50.1333	1.3411	**2.68%**
	P-34 (Transmission)	34.5418	0.8106	**2.35%**
	P-22 (T-3)	0.0000	0.0409	**#DIV/0!**
	P-23 (T-1)	0.0000	0.0216	**#DIV/0!**
	J-2689	12.4564	0.2604	**2.09%**
	J-809	8.4103	0.1058	**1.26%**
	J-4180	4.6454	0.0805	**1.73%**
	J-3999	4.6646	0.0801	**1.72%**
	J-5253	3.0761	0.0654	**2.13%**
	J-3896	6.8334	0.0978	**1.43%**
	J-4071	5.3131	0.0696	**1.31%**
	J-4069	9.5957	0.1136	**1.18%**
	P-24 (T-2)	0.0000	0.0240	**#DIV/0!**
	J-5421	8.6362	0.1542	**1.78%**
	J-4	31.9280	0.3681	**1.15%**
Pressure Summary	**Instruments**	**Experiment Average**	**Experiment Std Deviation**	**Std Dev/Average**
	J-3884	3.6062	0.0387	**1.07%**
	J-4090	23.3341	0.1740	**0.75%**
	J-5253	4.3086	0.0397	**0.92%**
	J-4	3.2666	0.0638	**1.95%**
	J-2418	3.5300	0.0410	**1.16%**
	J-5582	3.1259	0.0052	**0.16%**
	J-4180	8.6210	0.0697	**0.81%**
	J-809	0.0163	0.0198	**121.89%**
	J-2689	-0.5304	0.0311	**-5.86%**
	J-5421	4.5764	0.0635	**1.39%**
	J-3893	3.5963	0.0530	**1.47%**
	J-4186	4.0839	0.0289	**0.71%**
	J-3832	7.0193	0.1179	**1.68%**
	J-4181	4.9889	0.0929	**1.86%**
	J-4069	6.0597	0.1270	**2.10%**
	J-3999	4.7934	0.0646	**1.35%**
	J-3896	3.9798	0.0234	**0.59%**
	J-4071	9.5641	0.1187	**1.24%**
	J-5580	3.1480	0.0050	**0.16%**

KYPIPE model with the flows adjusted for flow balance and true demand flow measurements. The KYPIPE model was created using typical literature values of the minor loss components in the network.

KYPIPE Analysis for 6/20/2012 Experiment

The KYPIPE model developed for the experimental model was adjusted such that the specific demands from the experiment were added to the model. The levels from the tank meters were added as the initial tank levels within the model. The first two models varied only by the flow rates used as demands at the node, one set for the adjusted flows in the network and a model run using the flow rates as measured by the demands with no adjustment. The first two KYPIPE models were developed using the typical literature values for the minor losses and for the pipe roughness. A third KYPIPE model replaced literature values with the calibrated pipe roughness values. The performances of the three KYPIPE models are presented in table 19.

Table 19: Steady state 4 measured versus modeled pressure

		Model With Demands		Model With Adj Demand Flows For Flow Balance	
Node Name	**Measured Values (psi)**	**Modeled Values (psi)**	**Model To Measured Values %**	**Modeled Values (psi)**	**Model To Measured Values %**
J-2418	3.5300	3.56	**100.85%**	3.61	**102.27%**
J-2689	-0.5304	-0.29	**54.68%**	0.18	**-33.94%**
J-3832	7.0193	7.21	**102.72%**	7.43	**105.85%**
J-3884	3.6062	3.79	**105.10%**	4.15	**115.08%**
J-3893	3.5963	3.80	**105.67%**	4.16	**115.68%**
J-3896	3.9798	4.02	**101.01%**	4.06	**102.02%**
J-3999	4.7934	4.76	**99.30%**	5.13	**107.02%**
J-4	3.2666	3.44	**105.31%**	3.92	**120.00%**
J-4069	6.0597	7.15	**117.99%**	7.50	**123.77%**
J-4071	9.5641	10.27	**107.38%**	10.51	**109.89%**
J-4090	23.3341	19.75	**84.64%**	19.94	**85.45%**
J-4180	8.6210	8.68	**100.68%**	8.90	**103.24%**
J-4181	4.9889	5.05	**101.22%**	5.41	**108.44%**
J-4186	4.0839	4.28	**104.80%**	4.67	**114.35%**
J-5253	4.3086	4.41	**102.35%**	4.69	**108.85%**
J-5421	4.5764	5.27	**115.15%**	5.44	**118.87%**
J-5580	3.1480	3.15	**100.06%**	3.16	**100.38%**
J-5582	3.1259	3.15	**100.77%**	3.17	**101.41%**
J-809	0.0163	0.40	**2460.68%**	0.79	**4859.84%**
			Average		**Average**
			100.54%		100.48%

Table 19 Continued: Steady state 4 measured versus modeled pressure (continued)

		Model With Demands		Model With Demand C-factor Global	
Node Name	**Measured Values (psi)**	**Modeled Values (psi)**	**Model To Measured Values %**	**Modeled Values (psi) Cfact Global**	**Model To Measured Cfact Global %**
J-2418	3.5300	3.56	**100.85%**	3.55	**100.57%**
J-2689	-0.5304	-0.29	**54.68%**	-1.74	**328.08%**
J-3832	7.0193	7.21	**102.72%**	7.58	**107.99%**
J-3884	3.6062	3.79	**105.10%**	3.61	**100.11%**
J-3893	3.5963	3.80	**105.67%**	3.61	**100.38%**
J-3896	3.9798	4.02	**101.01%**	4.01	**100.76%**
J-3999	4.7934	4.76	**99.30%**	4.51	**94.09%**
J-4	3.2666	3.44	**105.31%**	3.23	**98.88%**
J-4069	6.0597	7.15	**117.99%**	6.54	**107.93%**
J-4071	9.5641	10.27	**107.38%**	10.99	**114.91%**
J-4090	23.3341	19.75	**84.64%**	21.22	**90.94%**
J-4180	8.6210	8.68	**100.68%**	9.01	**104.51%**
J-4181	4.9889	5.05	**101.22%**	4.65	**93.21%**
J-4186	4.0839	4.28	**104.80%**	4.09	**100.15%**
J-5253	4.3086	4.41	**102.35%**	4.30	**99.80%**
J-5421	4.5764	5.27	**115.15%**	5.36	**117.12%**
J-5580	3.1480	3.15	**100.06%**	3.14	**99.75%**
J-5582	3.1259	3.15	**100.77%**	3.14	**100.45%**
J-809	0.0163	0.40	**2460.68%**	-0.87	**-5351.97%**
			Average		**Average**
			100.54%		114.42%

Discussion of 6/20/2012 Experiment

The results of the experiment illustrated that KYPIPE and other water distribution programs matched the experimental physical data to a high average probability for this scenario. The KYPIPE model tended to over predict the pressures in the network using typical literature values and over predict more using global calibrated roughness values. Utilizing the pressure meters as the basis of the water surface elevations in the tanks corrected the inflows and outflows in the tanks and increased the correlation between the KYPIPE model and measured values.

The comparison of the results is presented in table 20. The results were on average about 0.54% higher than indicated by the experimental results for the demand-based KYPIPE model and slightly lower for the flow mass balance adjusted flow demands. The model that utilized the calibrated C-factors performed slightly worse than the model developed with typical literature values for pipe roughness and minor losses.

Steady State Hydraulics Analysis 5 (Flow Discrepancy Investigation)

Overview of the flow discrepancy experiment

The purpose of experiment was to investigate the flow discrepancy between the flow rates recorded by the demand nodes flow meters and the transmission line flow meters within the network lab pipelines upstream of the J-4069 and J-4071 demand nodes. The experiment was set up such that the only these two demand nodes were being supplied, as shown in figure 18. During the course of the tests, the gate valves at the J-4069 and J-4071 were progressively closed off by a single turn with data collected at each valve setting. The LabView model collected data using the fixed flow meters, and two handheld flow meters were utilized to simultaneously collect data during the experiment. The handheld devices were placed approximately halfway between the transmission lines and demand nodes to avoid any interference. The ultimate research objective of the tests was to investigate if the demand node flow meters are universally more accurate than the transmission line flow meters. It was important to investigate whether the accuracy of the transmission line flow meters was dependent on the valve settings or pressure within the network. In addition, new experimental regression equations were developed based on the results of these experiments to correct the flow discrepancy issue in the model.

Overview of the statistical analysis of the flow discrepancy experiment

A least squares regression analysis was performed within an Excel spreadsheet for the flow meters, tank level meters, and pressure meters datasets in each test series. The network was allowed to run for a short period of time (at least 5 minutes) before data collection. This allowed sufficient time for the network to reach steady state equilibrium after changing the boundary conditions.

The trends for each data series were removed from the individual time series by adjusting the dataset based on the linear trend slope and the distance from the average value for each time series. The methodology for the Fisher test as presented in the statistical analysis section of the report was the basis for determining the presence or absence of a trend.

Normality in the data was determined by examining the standardized residuals, which are the measured data points minus the regression predicted data points as a function of time and then divided by the standard deviation of the dataset. The normality methodology presented in the statistical analysis section of the report was the basis for analyzing normality in the data.

A check for a non-constant error variance was verified using the Szroeter test for non-constant variance. The data's error and variance were not found to meet the test statistic for non-constant variance for each of the test within the flow discrepancy experiments.

The physical model network was set up such that the flow from the J-4071 demand was supplied by the P-34 transmission line. Similarly, the J-4069 demand was supplied exclusively by P-38 transmission line. The flow rates from the experiment's mass balance had a variable discrepancy between the J-4071 demand node and the P-34 transmission line and a variable discrepancy between J-4069 demand node and the P-38 transmission line. Table 20 presents the discrepancy between demand nodes and transmission lines for each of the three experimental runs using the manufacturer's equation to determine the flow in the transmission lines.

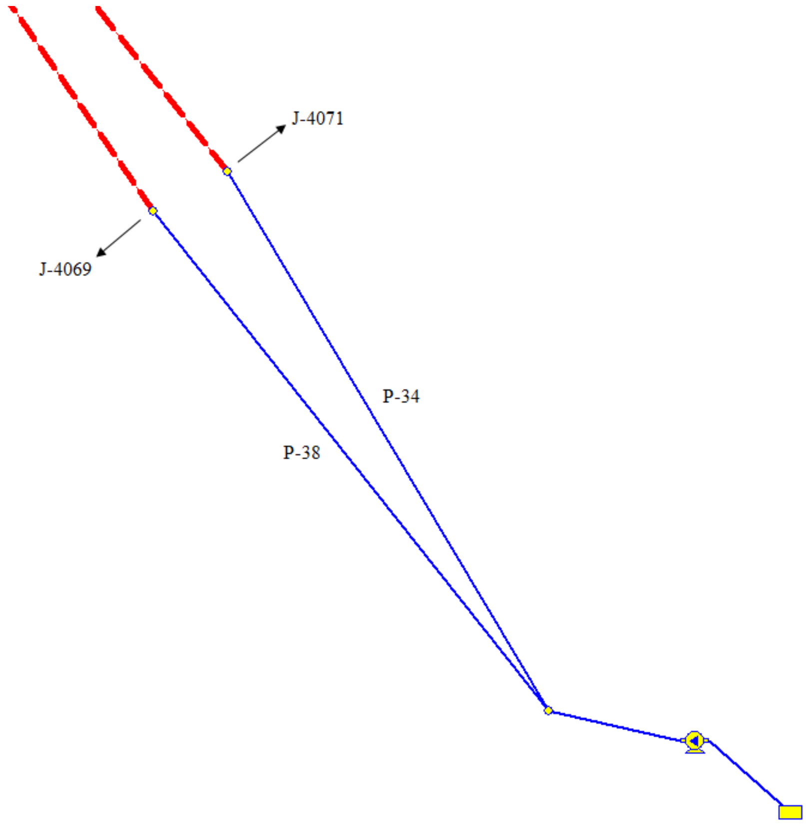

Figure 18: Schematic for flow discrepancy investigation

Table 210: Flow discrepancy using manufacturer's equation

Scenario 1: Pump valve fully open & 4.5 ft in reservoir (Manufacturer's Eqn)			
Number of Turns from open (demand valve)	**Difference between J-4071 & P-34 (GPM)**	**Difference between J-4069 & P-38 (GPM)**	**Total**
0	6.77	1.97	8.74
1	6.56	1.42	7.98
2	6.33	1.09	7.42
3	5.43	0.99	6.42
4	3.07	0.65	3.72
5	0.70	0.68	1.39

Scenario 2: Pump valve closed by 7 turns & 3.16 ft in reservoir (Manufacturer's Eqn)			
Number of Turns from open (demand valves)	**Difference between J-4071 & P-34 (GPM)**	**Difference between J-4069 & P-38 (GPM)**	**Total**
0	6.03	1.67	7.70
1	6.41	1.75	8.15
2	5.92	1.78	7.70
3	5.25	1.49	6.74
4	2.97	0.78	3.75
5	0.66	0.61	1.26

Scenario 3: Pump valve closed by 7 turns & 4.5 ft in reservoir (Manufacturer's Eqn)			
Number of Turns from open (demand valves)	**Difference between J-4071 & P-34 (GPM)**	**Difference between J-4069 & P-38 (GPM)**	**Total**
0	6.67	1.09	7.76
1	6.64	1.07	7.71
2	6.50	1.10	7.60
3	5.48	1.11	6.59
4	3.23	0.68	3.91
5	0.76	0.90	1.66

Overview of the KYPIPE Analysis

The KYPIPE models were created using typical literature values of the frictional and minor loss components in the network. The minor loss for the pump gate valve for each KYPIPE model was set to optimize the correlation between measured data and the modeled data. The flow results from the transmission lines are generated using a regression equation derived from experimental calibration. The discrepancy using the manufacturer's equations for the instruments for converting current into flow is larger than that of the experimental calibration. The comparison between the flow measurements using the manufacturer's equation and the calibrated regression are presented in table 21. The results aligned with previous experiments showing that the demand flow meters were more accurate to the true flow going through the network.

Four KYPIPE models were created for each set of data. One of the models utilized the unadjusted flow rates from the demand nodes flow meters. The second model used the flow rates as recorded by the transmission line flow meters. Ideally the flow rates for first and second model should be the identical. The third model utilized a flow adjusted average between the flow meter at the demand node and the transmission line that supply the demand node. The fourth KYPIPE model was based on the handheld ultrasonic flow meters recorded flow rates. The results of the four tests are presented in Appendix B. The value for the pump gate valve was adjusted for each test to give the data the highest possible agreement with the measured data. The results of the experiments indicate that the KYPIPE models using the demand flow meter measurements are in the best agreement for the measured pressure at the nodes in the network and this is independent of the valve setting used for the K factor minor loss for the pump gate valve.

A least squares regression analysis was performed to develop new regression equations for the flow transmission lines to correct the flow discrepancy. The currents were back-calculated from the previous experimentally developed regression equations. Then new experimental regression equations were developed based on the providing the best fit to the experimental results. The new regression equations were tested on several steady state simulations and were found to reduce the flow discrepancy between the sums of the demand node flow meters and the transmission flow meters in comparison with previous attempts to calibrate the flow meters to remove the flow discrepancy. A summary of that comparison is presented in table 22. The new regression equations are presented below:

$$Q_{P34} = 4368.505541 \times (Current) - 16.90695678 \qquad \text{Eq. 5}$$

$$Q_{P38} = 4811.162099 \times (Current) - 18.52900630$$

Table 221: Flow discrepancy using calibrated regression

Scenario 1: Pump valve fully open & 4.5 ft in reservoir (calibrated regression)			
Number of Turns from open (demand valves)	**Difference between J-4071 & P-34 (GPM)**	**Difference between J-4069 & P-38 (GPM)**	**Total**
0	1.08	-0.32	0.77
1	1.30	0.22	1.51
2	1.10	0.46	1.57
3	0.65	0.33	0.97
4	0.06	0.18	0.23
5	0.02	-0.17	-0.15

Scenario 2: Pump valve closed by 7 turns & 3.16 ft in reservoir (calibrated regression)			
Number of Turns from open (demand valves)	**Difference between J-4071 & P-34 (GPM)**	**Difference between J-4069 & P-38 (GPM)**	**Total**
0	1.12	-0.13	0.99
1	0.75	-0.22	0.54
2	0.89	-0.32	0.57
3	0.49	-0.21	0.27
4	0.09	0.05	0.13
5	0.07	-0.09	-0.02

Scenario 3: Pump valve closed by 7 turns & 4.5 feet in reservoir (calibrated regression)			
Number of Turns from open (demand valves)	**Difference between J-4071 & P-34 (GPM)**	**Difference between J-4069 & P-38 (GPM)**	**Total**
0	0.64	-0.47	0.17
1	0.63	-0.47	0.16
2	0.51	-0.38	0.14
3	0.35	-0.17	0.18
4	-0.06	-0.13	-0.19
5	-0.04	0.38	0.34

Table 232: Flow discrepancy summary

	Discrepancy (GPM)	
Test	**Old Regression**	**New Regression**
C-Factor Config #3	0.68	0.00
C-Factor Config #9	2.02	0.77
C-Factor Config #2	0.76	-0.04
7-10-2012 Steady State	3.44	1.90
6-6-2012 Steady State	8.66	4.39

Tracer Injection

After verification of the hydraulic results of the model, the next step is to perform a tracer study using the lab model. For each of the three tracer experiments presented in this section, a calcium chloride solution was injected downstream of the pump. To keep the studies consistent, each solution was made of 0.755 grams of calcium chloride per liter of water, and was injected over a duration of 80 seconds. The next sections present the results of a tracer study performed on the laboratory water distribution model.

Water Quality Tracer Study 1

The network was first set up to reach a steady state condition by turning on the pump and adjusting the gate valves at the outflow locations. Each of the storage tanks were monitored until their water surface elevations no longer increased or decreased. Approximately 7.875 liters of a tracer solution containing 0.755 g/L of calcium chloride was injected about 3.5 feet downstream of the pump over a total duration of 80 seconds. Six electrical conductivity meters were placed throughout the network; one sensor was placed upstream of the injection pump in order to model the continuous rise in the background concentration of calcium chloride. Figure 19 shows the network configuration and the locations of the remaining five sensors throughout the network. All the pipes, tanks, and outlets in the network were open. Table 23 shows the outflow at each demand node and the tank levels for this tracer simulation.

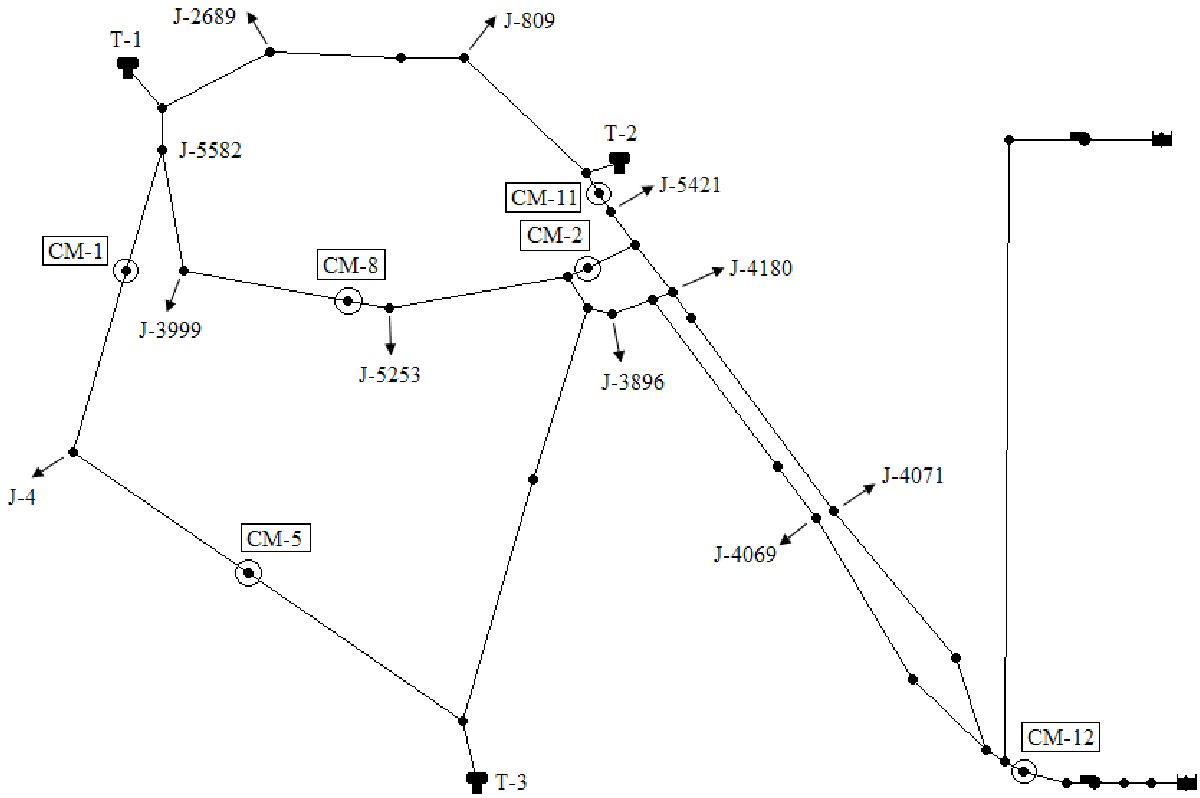

Figure 19: Conductivity Meter Locations

Table 243: Water quality tracer 1 boundary conditions

Node	*Outflow (gpm)*
J-2689	3.387
J-809	3.728
J-4180	8.549
J-3999	1.617
J-5253	1.961
J-3896	30.237
J-4071	14.253
J-4069	26.030
J-5421	7.060
J-4	18.200

Tank	*Depth (ft)*
Reservoir	1.990
T-1	1.698
T-2	2.298
T-3	2.060

The sensor at location CM-12 collected data that showed the rising concentration of calcium chloride in the network. These data were then input into the source reservoir as a time series pattern of the maximum background concentration (as described previously). Figure 20 shows the input and output of this data set.

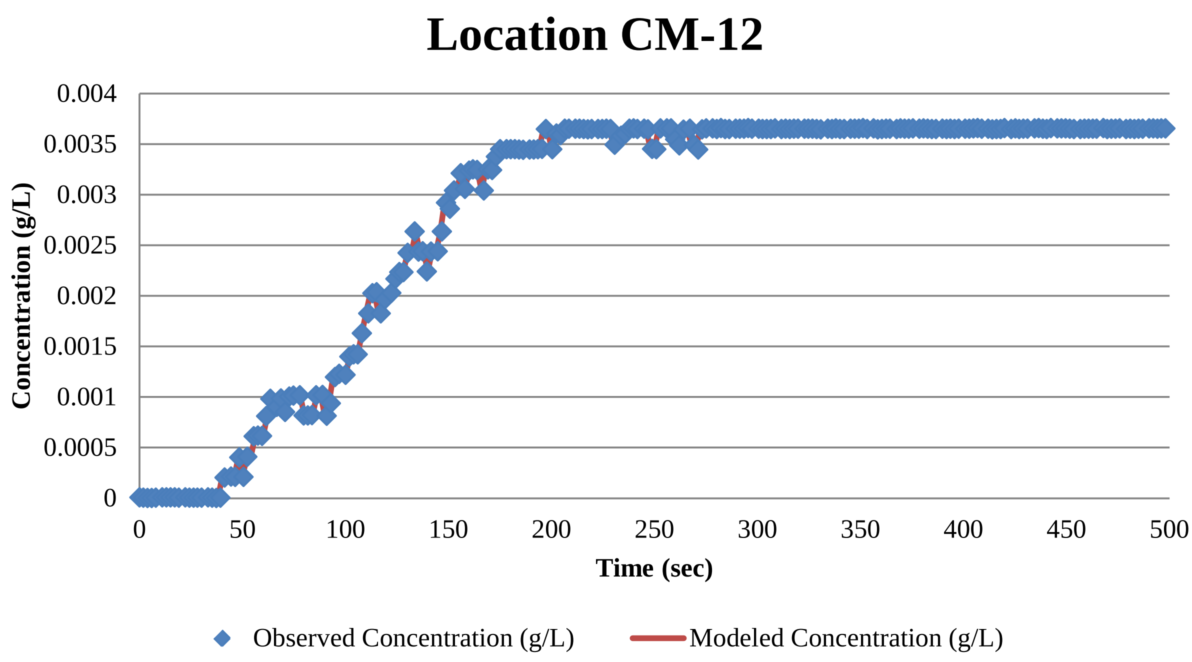

Figure 20: Background concentration of calcium chloride

Figures 21 – 25 show the calcium chloride concentration over time at each sensor location throughout the network.

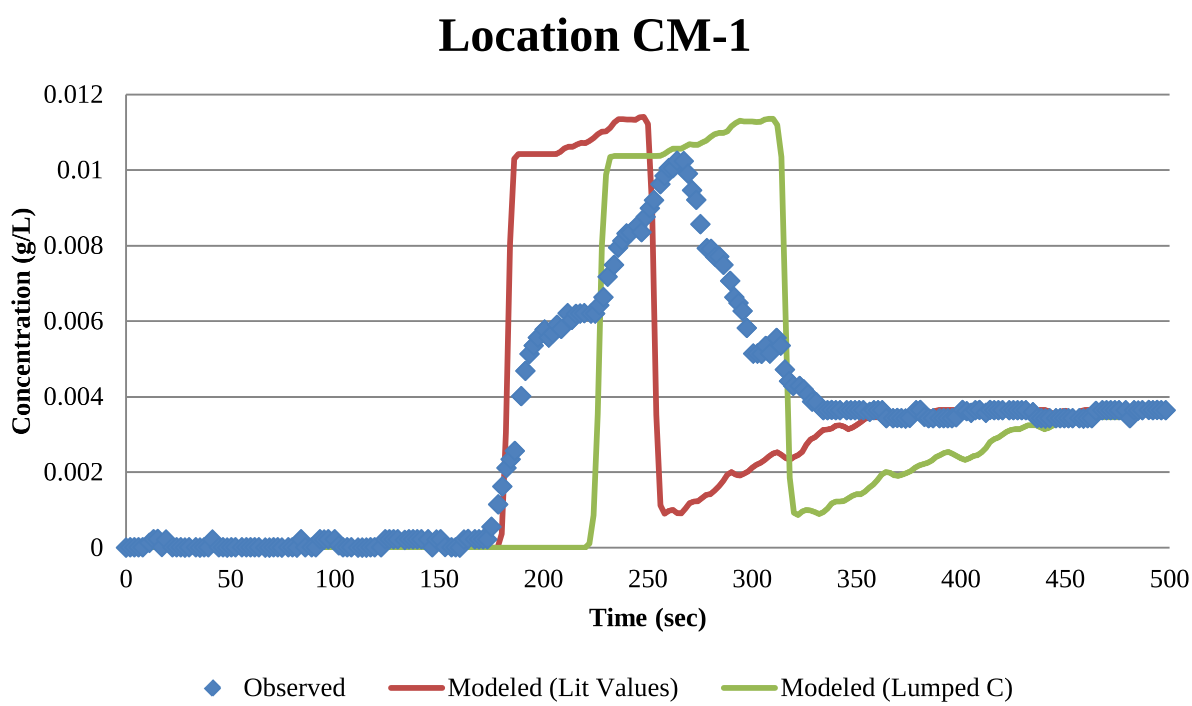

Figure 21: Calcium chloride concentration at position CM-1

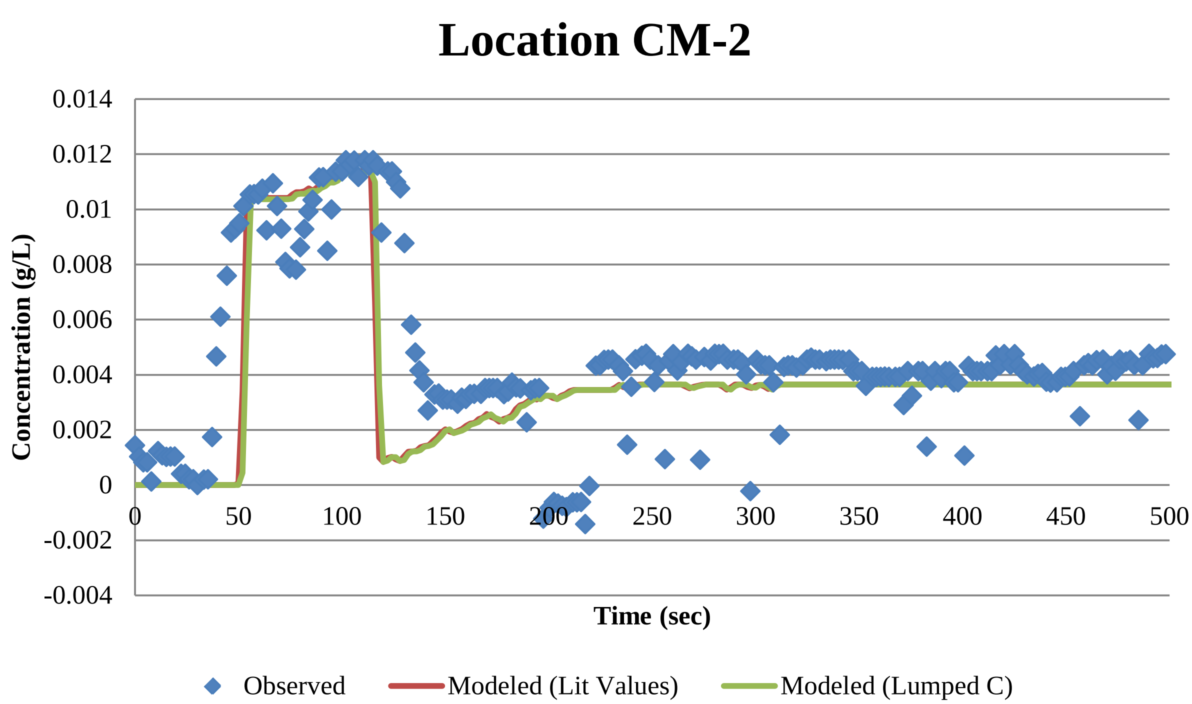

Figure 22: Calcium chloride concentration at position CM-2

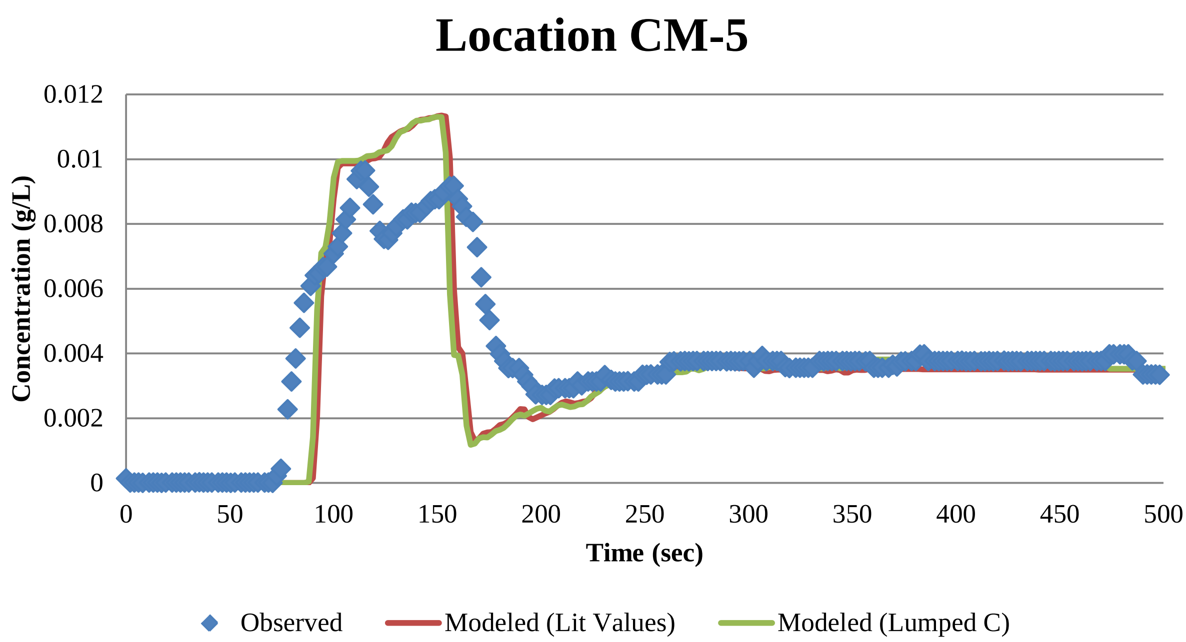

Figure 23: Calcium chloride concentration at position CM-5

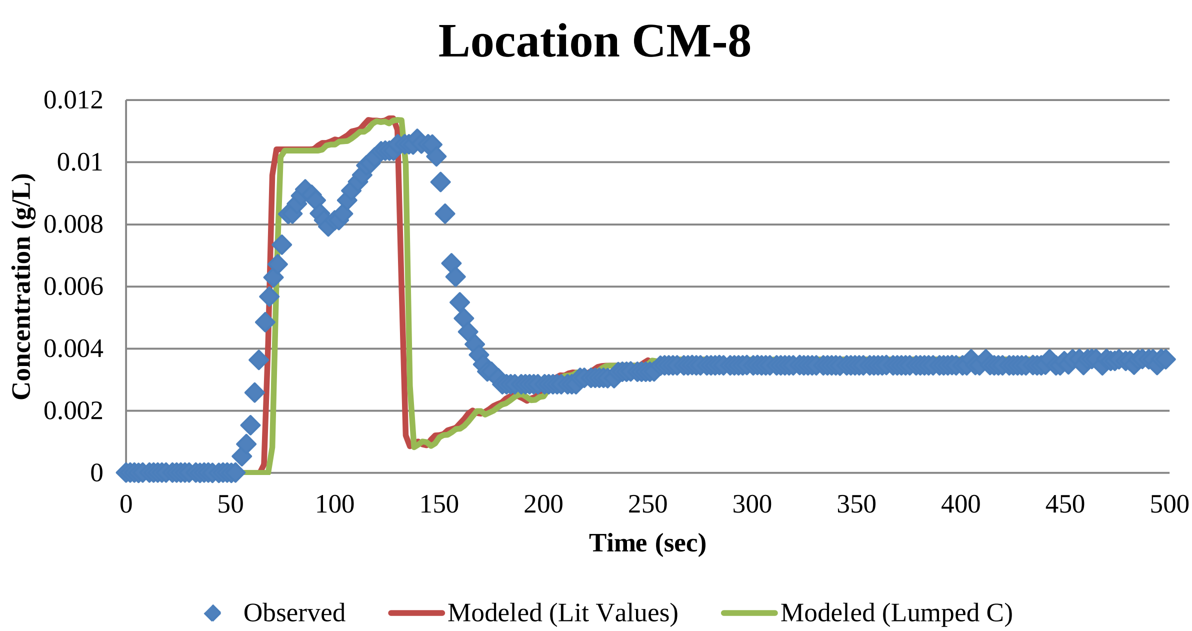

Figure 24: Calcium chloride concentration at position CM-8

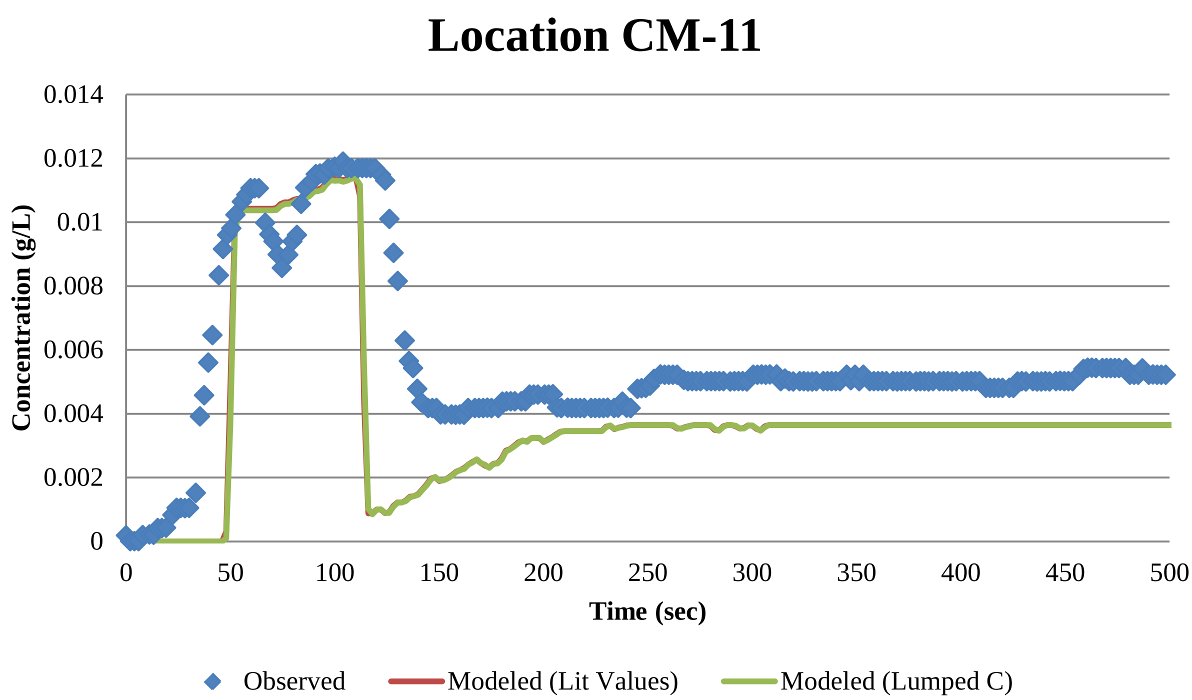

Figure 25: Calcium chloride concentration at position CM-11

Discussion

These results show that the model is able to predict the transport of a tracer through the network with a reasonable degree of accuracy. However, the deficiency of the model is that the tracer was detected before predicted at every location. This is especially apparent at location CM-1. This is likely a hydraulic calibration issue; while the lumped C-factor approach that was used accounts for minor losses, it does not address the spatial distribution of the minor losses. On the other hand, the model that used the literature values for the minor and frictional losses was able to predict the timing of the beginning of the tracer plug, but did not correctly predict the shape of the curve. In reference to figure 19, both models show the tracer moving from J-4 to the junction J-5582. However, as evidenced by the observed data shown in figure 21, the flow must have been coming from two directions. This means that rather than flowing from J-4 toward J-5582, the water was actually flowing in the opposite direction, allowing the flow to combine at the junction J-5582. This created the two separate waves of the tracer, as seen in figure 21. Since the pipe diameters of the model are so small, the minor losses have more of an impact on the modeling results than they do in a full size water distribution system. Therefore, a more accurate representation of the minor losses in the network may be necessary to fully represent the water quality aspects of the network.

Water Quality Tracer Study 2

This section shows the results of the second tracer analysis performed on the laboratory model. First, the pump was turned on and the valves adjusted so that the system was able to reach steady state. Once this steady state condition was reached, a calcium chloride solution was injected about 3.5 feet downstream of the pump. Approximately 6.68 liters of the solution, which had a calcium chloride concentration of 0.755 g/L, was injected over a duration of 80 seconds. Five electrical conductivity sensors were placed throughout the system to obtain information about how the tracer disperses through the network. A sixth conductivity meter was located immediately upstream of the point of injection to allow for observation of how the background concentration of calcium chloride in the system rises during the experiment. Figure 26 shows the configuration of the network and the locations of the conductivity sensors. All of the pipes, tanks, and demand valves in the network were open for this simulation. The outflow at each node and the depth of water in each tank is shown in table 24.

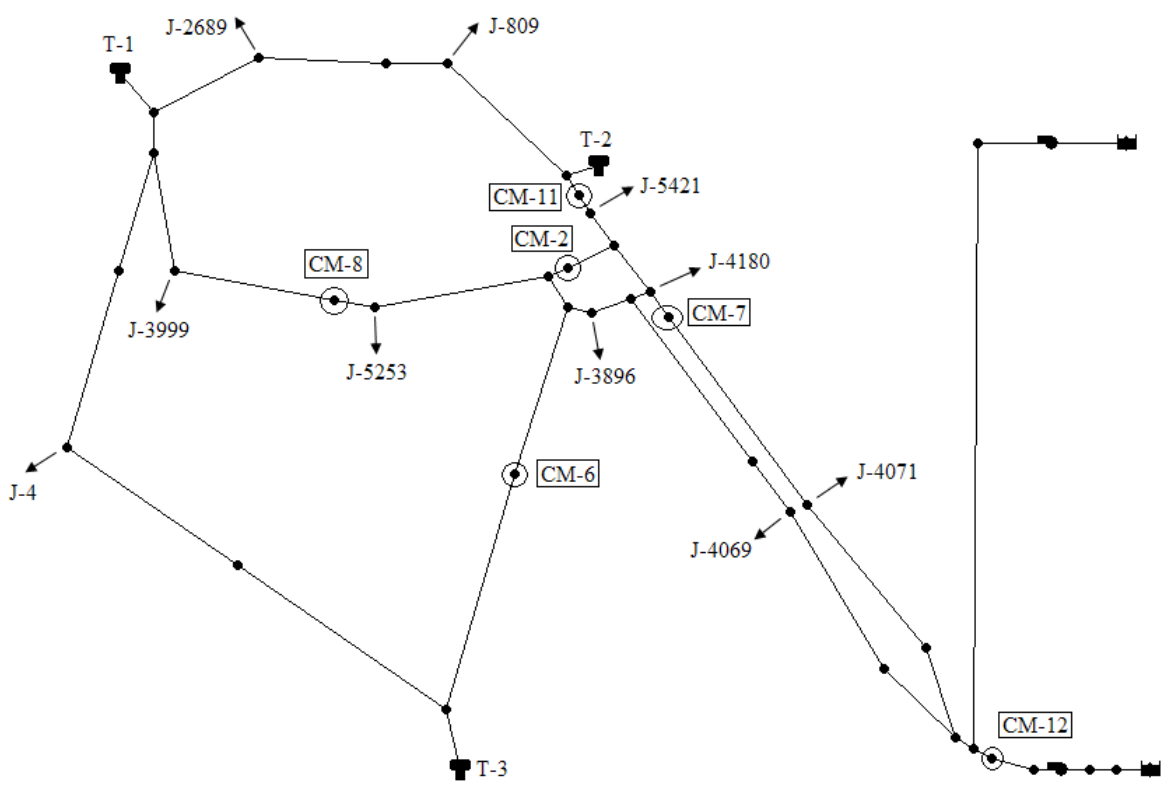

Figure 26: Conductivity Meter Locations

Table 254: Water quality tracer 2 boundary conditions

Node	***Outflow (gpm)***
J-2689	3.733
J-809	5.955
J-4180	1.743
J-3999	2.768
J-5253	6.928
J-3896	31.581
J-4071	15.140
J-4069	25.888
J-5421	6.246
J-4	17.889

Tank	***Depth (ft)***
Reservoir	3.691
T-1	1.111
T-2	2.213
T-3	1.766

Figure 27 shows the measured and modeled background concentration of the network, as observed from sensor location CM-12. These data were input into the reservoir as a time series of concentration.

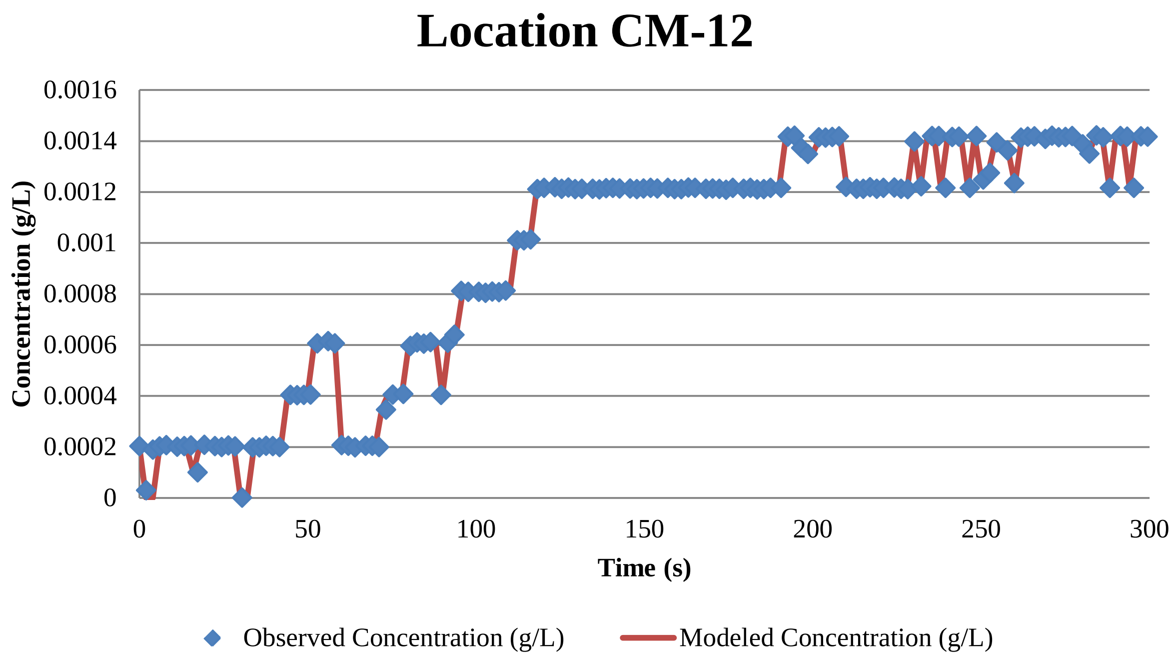

Figure 27: Background calcium chloride concentration

Figures 28–32 show the results of the tracer study from the perspective of each of the conductivity meters.

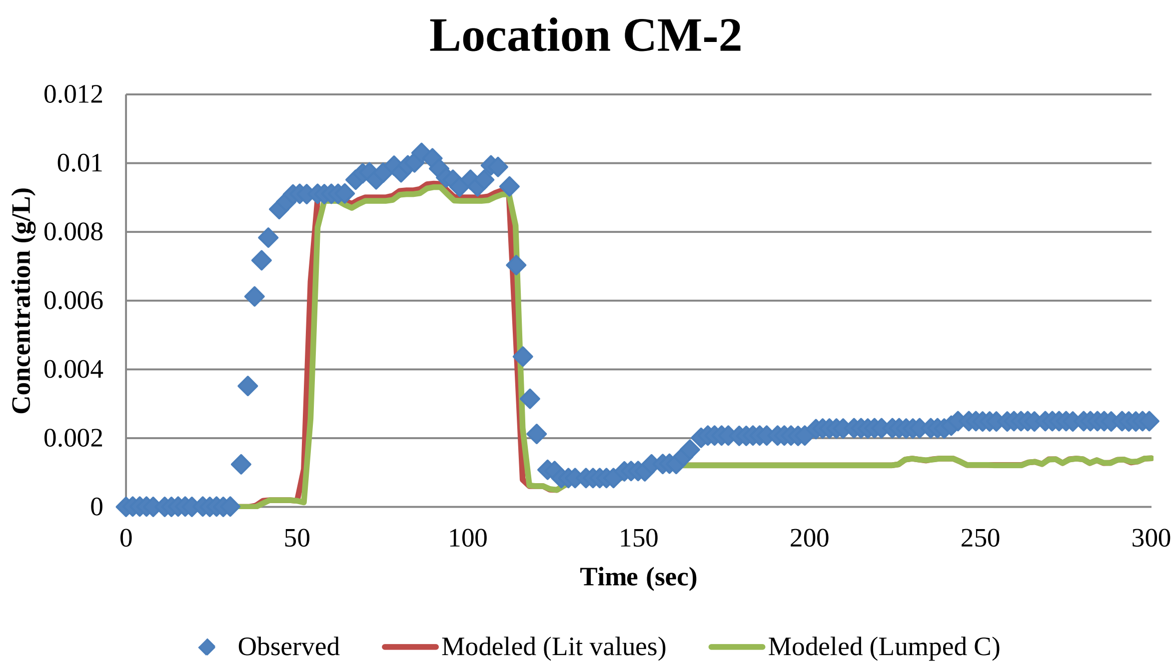

Figure 28: Calcium chloride concentration at position CM-2

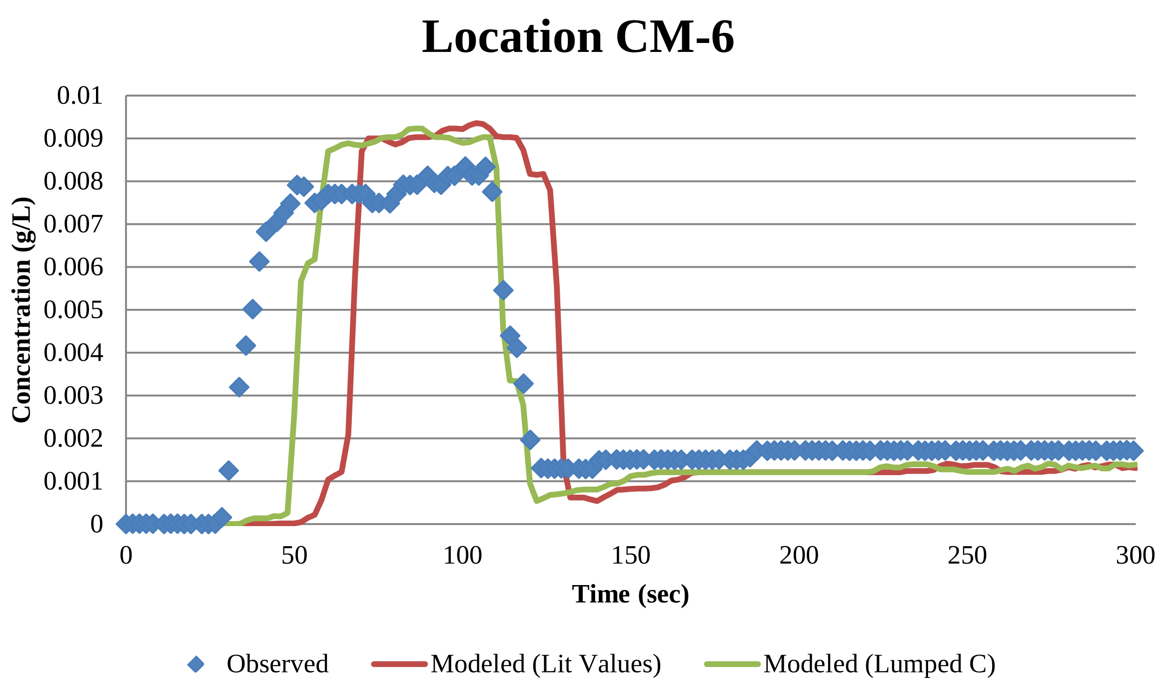

Figure 29: Calcium chloride at position CM-6

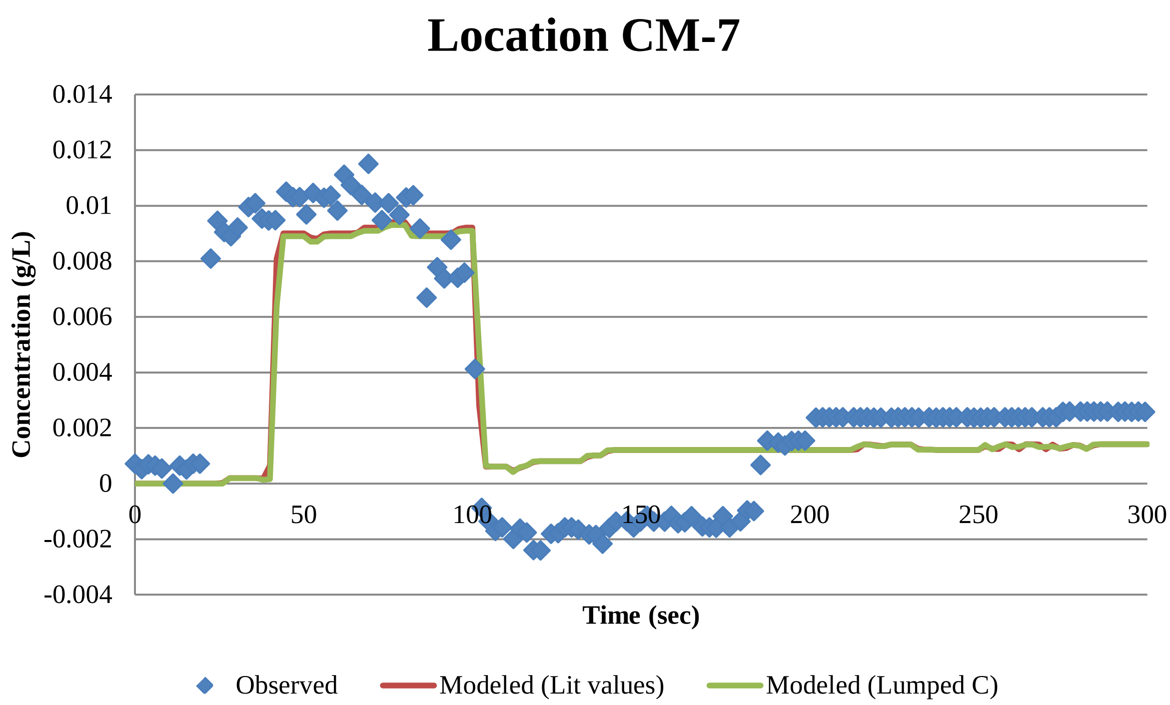

Figure 30: Calcium chloride concentration at position CM-7

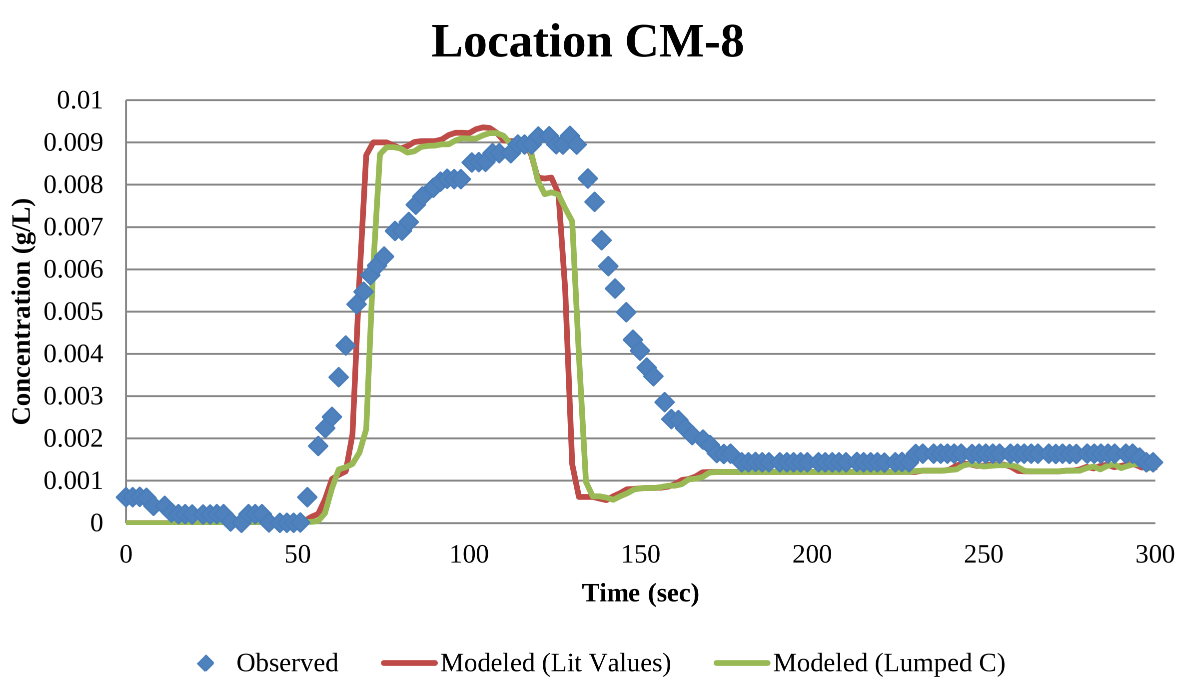

Figure 31: Calcium chloride concentration at position CM-8

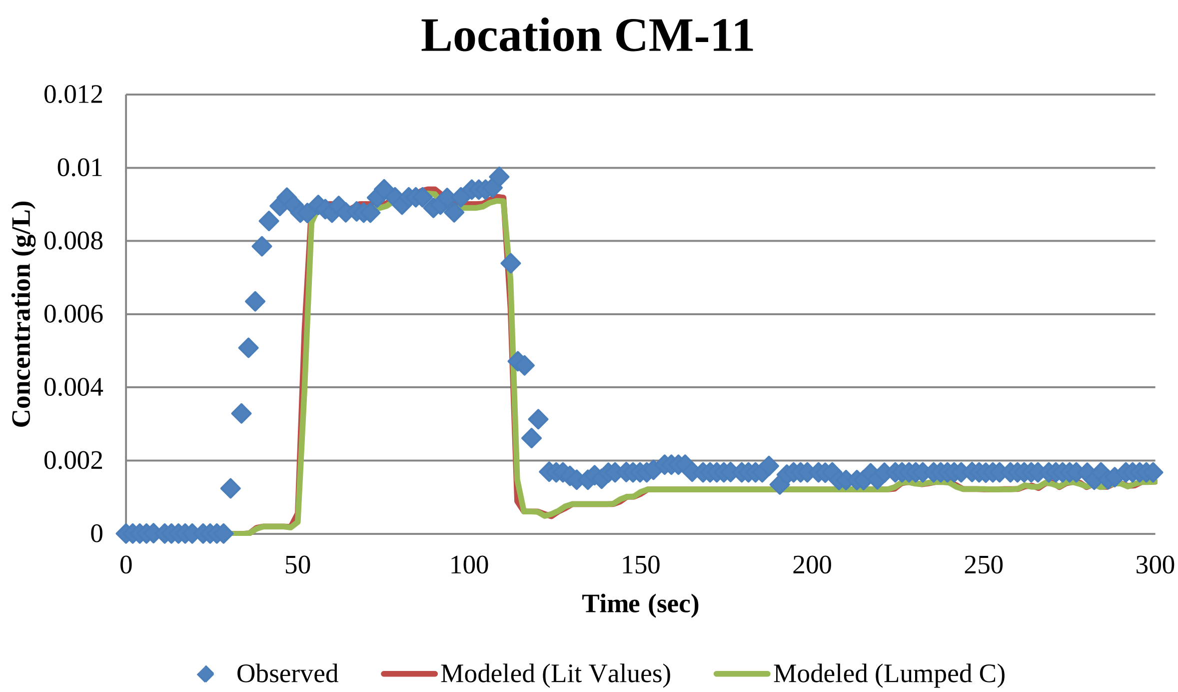

Figure 32: Calcium chloride concentration at position CM-11

Discussion

As shown by figures 28 – 32, the model was able to predict the transport of calcium chloride through the network with reasonable accuracy. The model shows deficiencies, however, in predicting the elapsed time to detection. At every sensor location in the network, the model predicted the tracer to be detected later than the data showed, indicating that the model is showing lower velocities throughout the network that originate from the source. This is further evidenced by the fact that the model shows the elevated tanks to be draining by as much as 3.4 GPM, when in reality they were at a steady state condition. This issue is likely a consequence of the method used for the hydraulic calibration. Since the pipe diameters are all 2 inches or less, the minor losses have a higher contribution than they do in a full-scale network. Therefore further work may be necessary to calibrate minor loss coefficients that more accurately represent the losses in the network. Both models predicted nearly equivalent water quality results, with the exception of the monitoring location CM-6. The lumped C-factor model predicted the tracer at CM-6 more accurately than the model that used literature values. This resulted from the lumped C-factor model predicting a higher flow in the left transmission line, resulting in higher velocities through the left portion of the network. This implies that while the model that used the literature values accounted for the spatial distribution of minor losses, the coefficients that were used were not close enough to the true coefficients. Another apparent deficiency is seen in the data at monitoring position CM-7. After the tracer passes through the point of observation, the concentration of calcium chloride appears to drop to a negative number. In reality, the conductivity meters often experience some air entrainment, which causes them to output very low or no conductivity. The negative numbers that appear in the graph are a result of skewed readings after the baseline concentration is subtracted off of the data.

Water Quality Tracer Study 3

This section presents the results of a water quality simulation run using the laboratory model. Prior to water quality data being collected, the pump was turned on and valves adjusted such that the system could reach a steady state condition. Incoming data was observed to verify that the system had reached steady state, and then a calcium chloride solution was injected about 3.5 feet downstream of the outlet of the pump. There were six electrical conductivity meters distributed throughout the network, one of which was immediately upstream of the point of injection. This gave the information for a time series of the background level of calcium chloride. Figure 33 shows a schematic of the system with the locations of the conductivity meters marked. All of the pipes, tanks, and outlets were active during this experiment. Table 25 shows the outflow at each node and the depth in each tank for this water quality simulation.

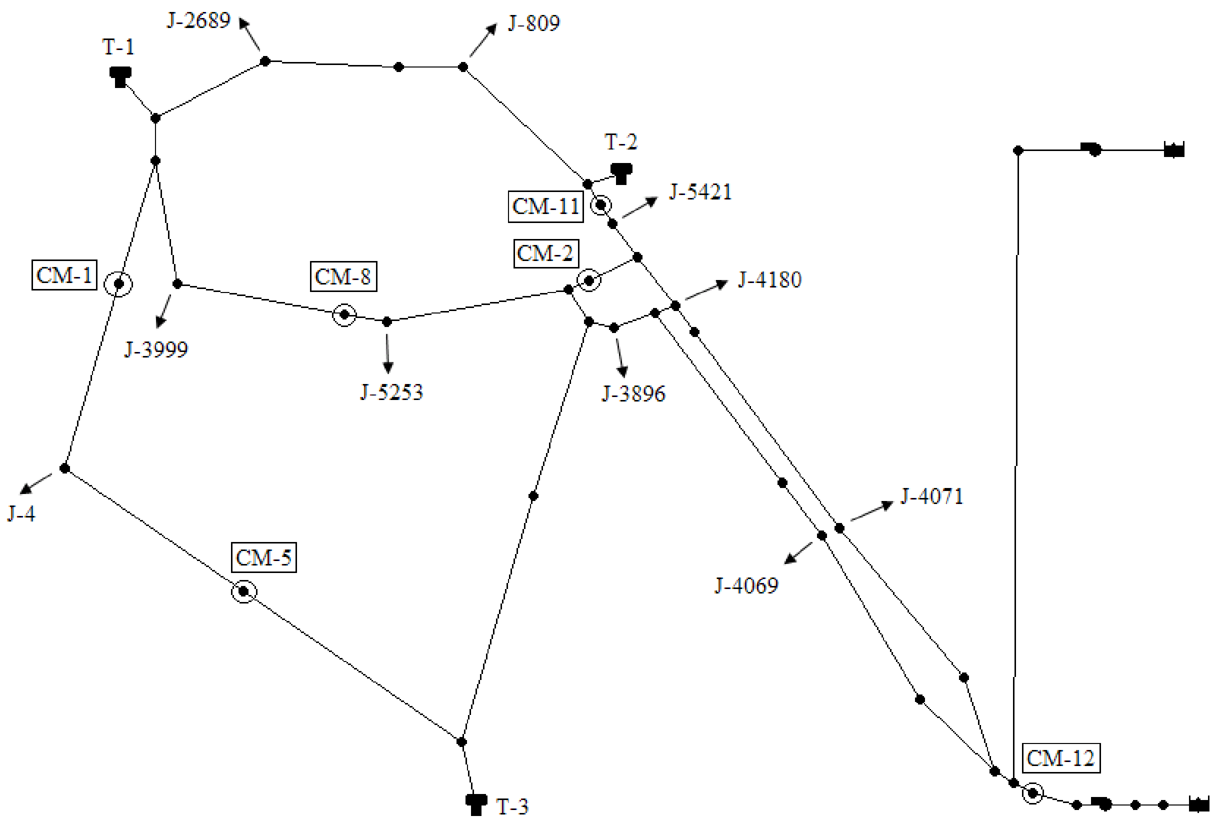

Figure 33: Conductivity Meter Locations

Table 265: Water quality tracer 3 boundary conditions

Node	***Outflow (gpm)***
J-2689	2.10459
J-809	1.88949
J-4180	2.5457
J-3999	4.06645
J-5253	2.49673
J-3896	27.0956
J-4071	5.33187
J-4069	26.3957
J-5421	12.2219
J-4	30.0281

Tank	***Depth (ft)***
Reservoir	2.47976
T-1	0.95888
T-2	1.76273
T-3	1.51708

The tracer was an aqueous solution that contained 0.755 g/L of calcium chloride. Approximately 7.18 liters of solution was injected continuously over a period of 80 seconds, which is modeled as a pump (represented in the top-right corner of figure 33) with a constant flow rate of 1.42 GPM. A control has been placed on the model to close off the discharge line of the pump after 80 seconds. Since the outlets of the system ultimately discharge back to the reservoir, a time series of the background level of calcium chloride has been input into the model at the reservoir using the data collected at the location CM-12. Figure 34 shows the observed and modeled background concentration of the model.

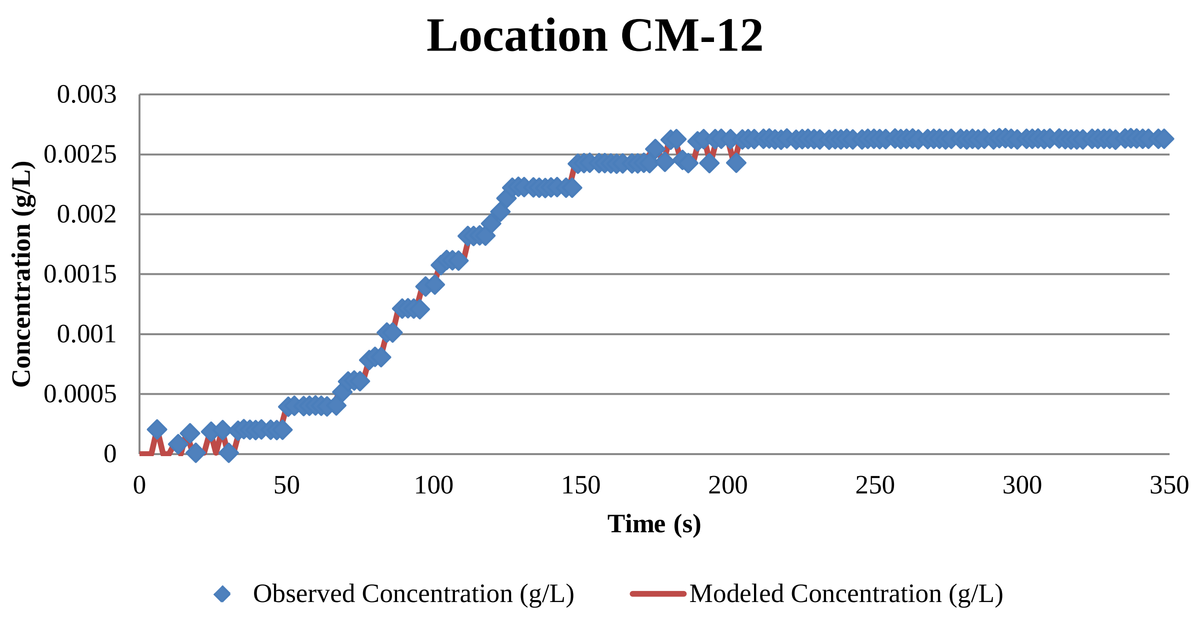

Figure 34: Background Concentration

The comparison between the modeled and measured concentrations of the tracer is made by observing the time-series of concentration at the fixed locations throughout the network. For every location, the model predicted the spike in conductivity to arrive later than it actually did. Table 26 shows the measured and modeled elapsed times before the solution arrived at each location.

Table 276: Time to Detection

Sensor Location	*Modeled Elapsed Time, Lumped C-factor (sec)*	*Modeled Elapsed Time, Literature Values (sec)*	*Observed Elapsed Time (sec)*
CM-11	38	38	34
CM-8	56	49	48
CM-1	153	129	118
CM-5	67	67	56
CM-2	42	40	36

Figures 35 – 39 show the observed and modeled calcium chloride concentrations as the tracer passes through each sensor location.

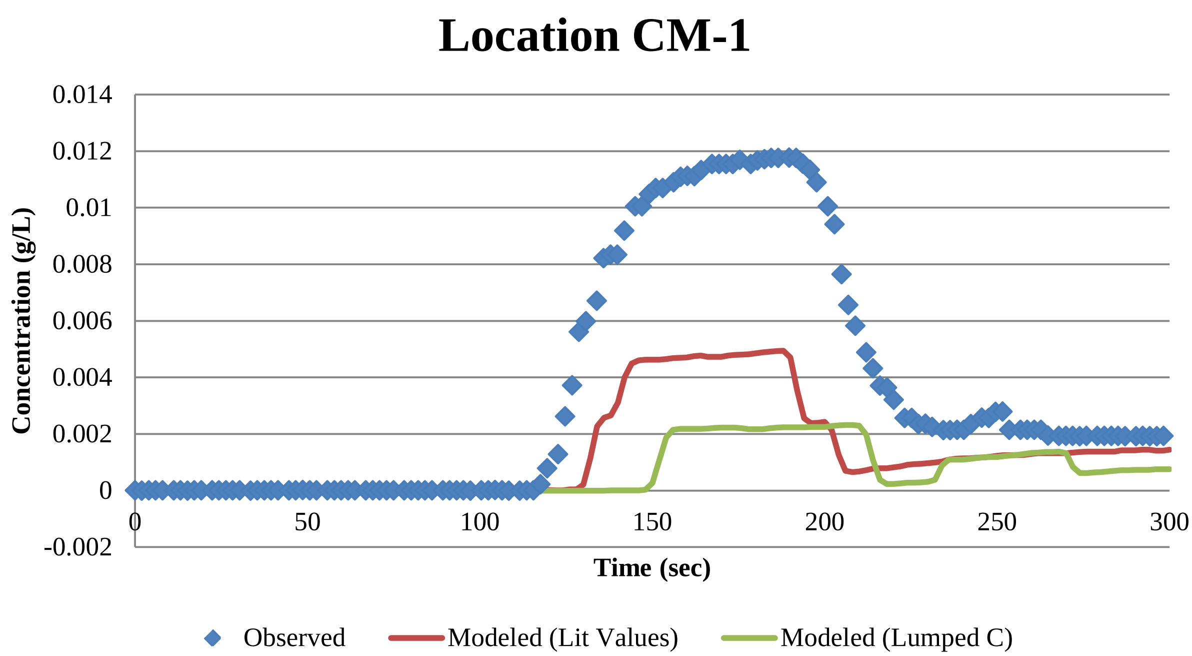

Figure 35: Concentration at position CM-1

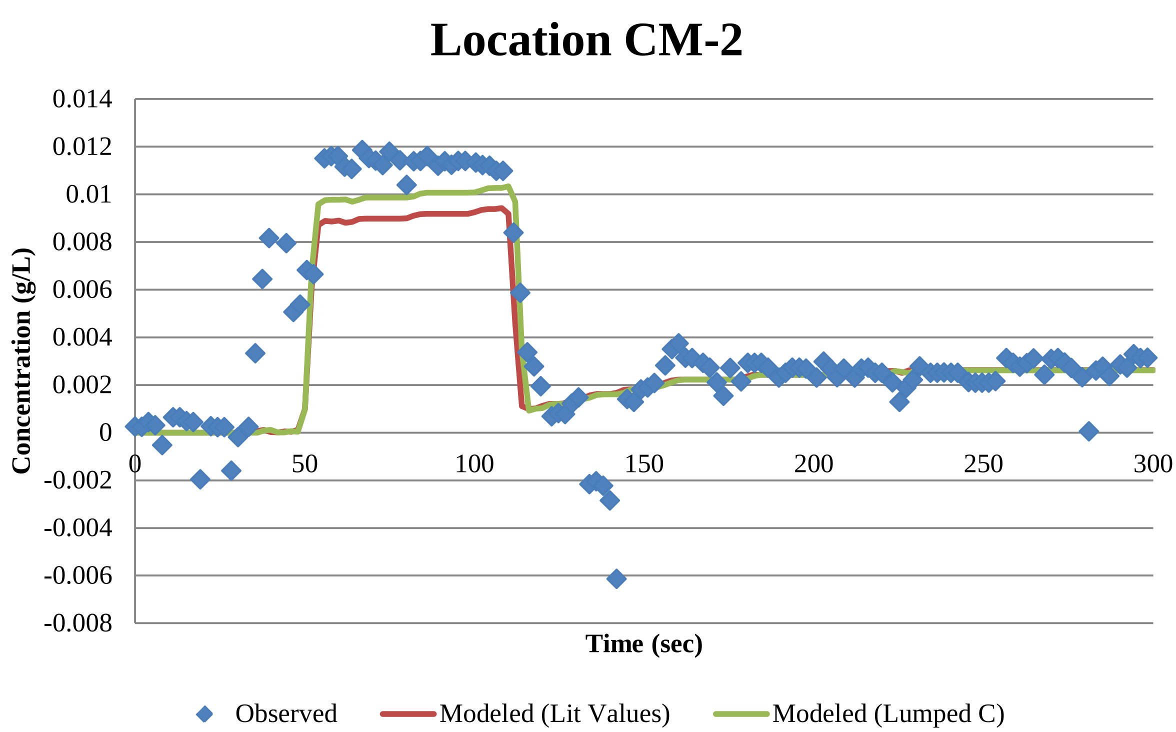

Figure 36: Concentration at position CM-2

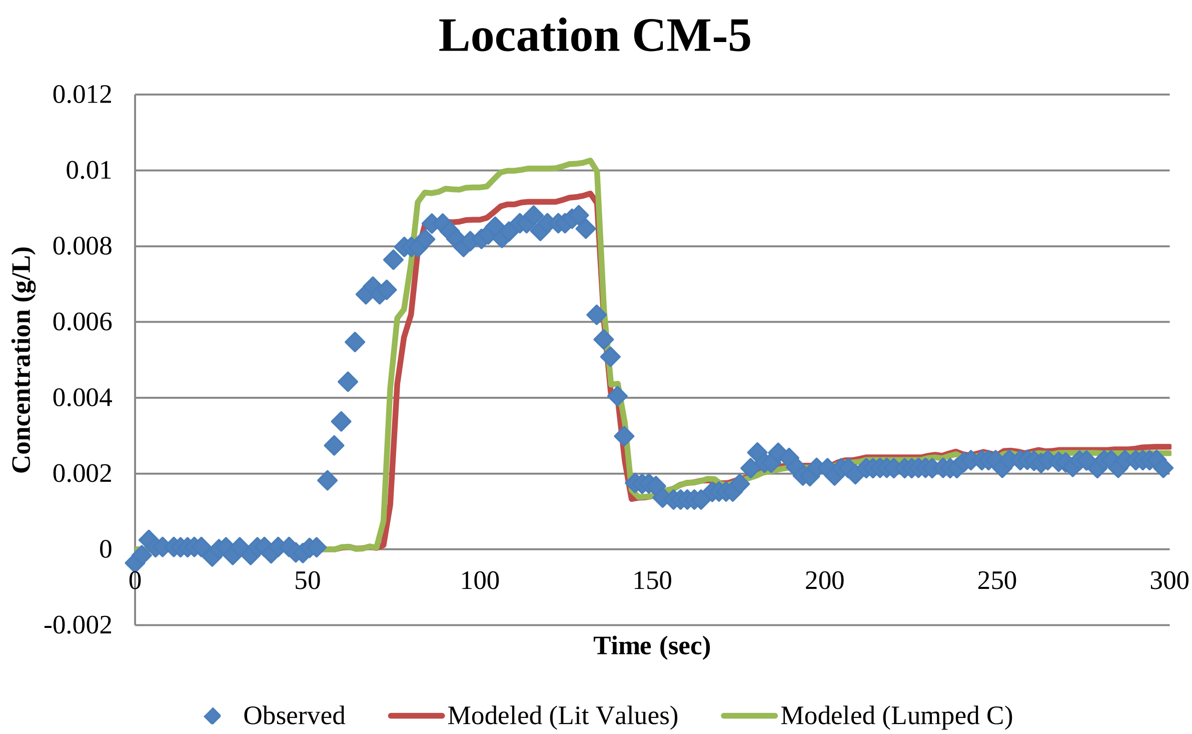

Figure 37: Concentration at position CM-5

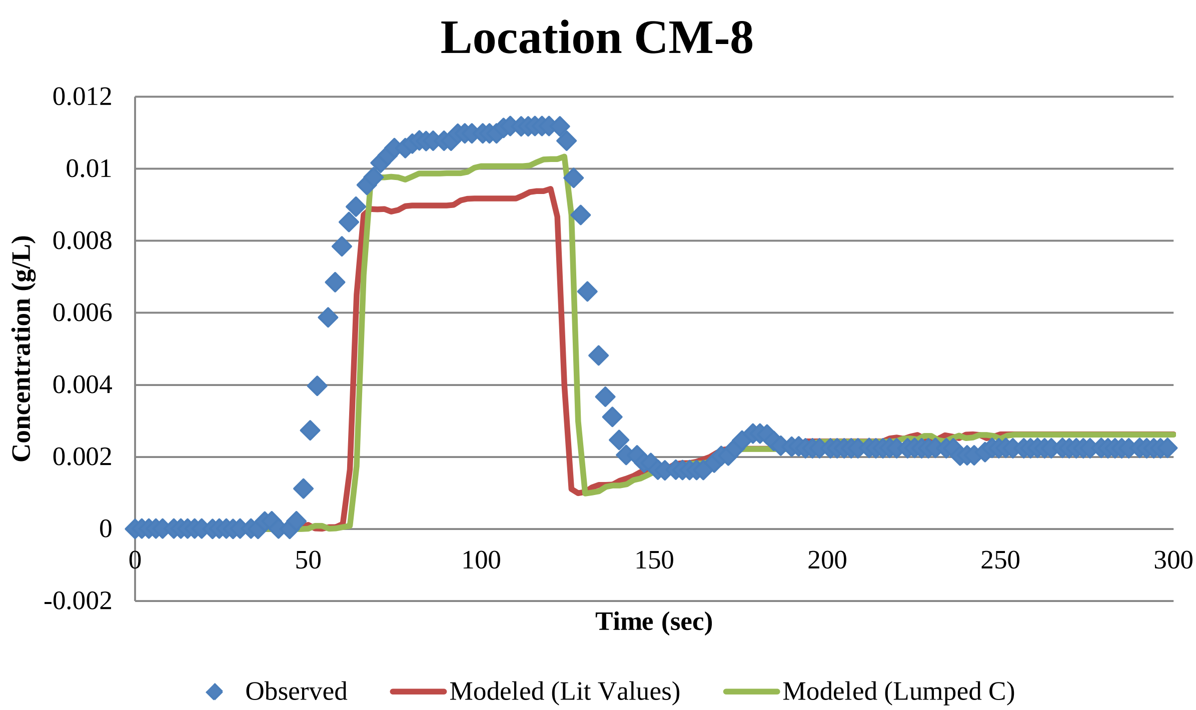

Figure 38: Concentration at position CM-8

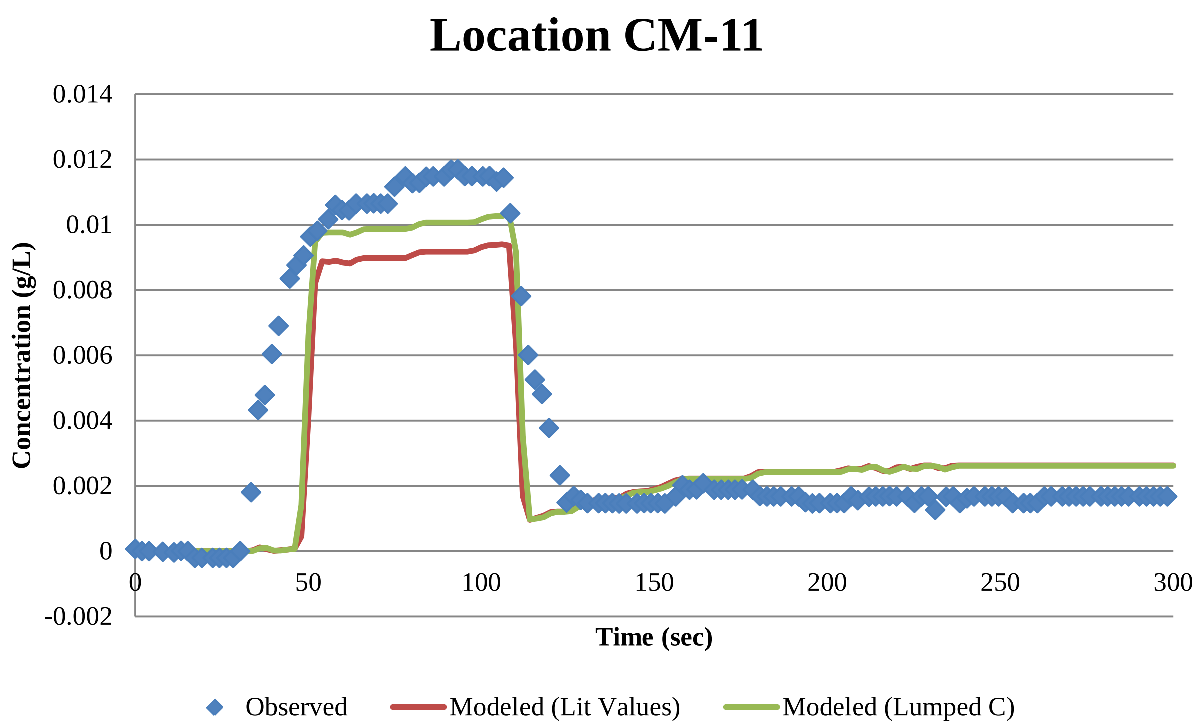

Figure 39: Concentration at position CM-11

Discussion

It is evident that both models were able to predict the timing and magnitude of the tracer with reasonable accuracy, with the exception of one location. At position CM-1, both models severely underpredicted the results, which would seem to invalidate the model had this been the only site of investigation. However, the hydraulic results of both models show that the elevated storage tank on the upper left side of the schematic is draining. The model with the literature values shows it to be draining at a rate of about 1.5 GPM, while the lumped C-factor model shows it to be draining by about 2.5 GPM. This would cause the site CM-1 to be supplied by uncontaminated water from the tank, which explains why the lumped C-factor model predicted a lower peak concentration at CM-1. More flow from the tank in the lumped C-factor model would cause site CM-1 to become diluted by clean water, lowering the peak concentration. In reality, the tank was not draining, and CM-1 was only supplied with contaminated water from the pump. The model that utilized the lumped C-factors outperformed the other model at sites CM-2, CM-8, and CM-11. These deviations are most likely a result of slight inaccuracies in both methods of hydraulic calibration. This shows that an accurate hydraulic model is imperative to the development of an accurate water quality model.

Conclusions

Two methods of hydraulic calibration have been presented in this report. The first utilizes an enumeration of all the components of the physical system that contribute to minor losses. The second method utilizes a lumped C-factor approach that is widely used in the calibration of full-scale water distribution system models. Upon examination of the hydraulic and water quality results, both models were able to replicate reality with reasonable accuracy but it is unclear which one outperformed the other. In fact, both gave nearly identical results for the majority of the water quality sensor locations.

Future Work/Issues

The results presented in this document indicate that hydraulic modeling software, such as KYPIPE or EPANET, can predict hydraulic and water quality characteristics of a water distribution system with reasonable accuracy. However, there is still room for improvement. The models presented employed the generally accepted method of calibration, which involved calculating three different C-factors that lumped in all potential losses in the pipe. Because of this method of calibration, the model has no way of distinguishing between the relative losses of two pipes of the same size. This is partially alleviated by using minor loss coefficients commonly found in literature to represent the fittings, elbows, tees, etc. that are in the network. However, since these coefficients have a larger impact on smaller diameter pipes than larger diameter pipes, they may not accurately represent the true energy losses of the components in the system. In addition, the minor loss coefficients for the data acquisition instruments in the system, which intrude into the flow field, are unknown. This led the research team to construct a second system specifically for the purpose of determining the minor loss coefficient of every component in the network.

This setup consists of three sections. The first section, constructed from 2” diameter PVC pipe, consists of the pump, two gate valves, and a pressure sensor. One of the gate valves is used to throttle the flow; the other gate valve is located on a pipe section perpendicular to the main pipe. It is connected by a tee that is placed between the pump and the flow throttle gate valve. This valve is primarily used to adjust the pressure of the system by diverting the flow. Downstream of the tee is a pressure sensor. At the end of the first section is a flange that connects the upstream section with a temporary experimental section. The test section is connected via a flange on both ends. Downstream of the test section is the outlet section, which houses another pressure sensor and another gate valve. This downstream gate valve is used to pressurize the system.

The test section of the system consists of a five foot span of PVC pipe. There are three pipe sizes used in this experimental setup: 1”, 1½”, and 2”. Each size pipe has a blank section in which the losses across only the PVC pipe are tested. Each component to be tested is placed in the center of a test section such that the same length of pipe is used in every test element allowing for the true minor loss of a component to be calculated by subtracting off the corresponding minor loss value of the blank section. This setup is part of an ongoing effort to calibrate the hydraulic model as closely as possible with the laboratory setup. The results have not yet been used in the model, but will help contribute to the understanding of the contribution of minor losses in the model.

Another method of calibration that is currently being explored involves using the water quality data to calibrate the hydraulics of the model. This can be used to determine the true flow distribution of the network. For example, if the tracer data show two spikes in concentration, then that sensor must be receiving flow from two different flow paths simultaneously. Two distinguishable spikes in concentration would show up because one of the flow paths from the source is slower than the other. Based off this information, a new injection point can be set up strategically in a different location to determine the flow paths and velocities within the network. This should give further insight into the flow dynamics and will give more basis for comparison of the data with the model.

Appendix A: Experimental Procedures

General System Information

The pipe network was designed to serve as a rudimentary scaled model of a moderately sized water utility. The network is complete with a water reservoir, storage tanks, and demand nodes. The final constructed model consists of approximately 470 feet of PVC pipe, 10 demand nodes, and 3 storage tanks. The system network is supplied with a 900 gallon reservoir and three horsepower pump that can deliver up to 120 GPM to 10 demand nodes and 3 different storage tanks. The system is located along the western wall of the University of Kentucky Hydraulics Laboratory. The majority of the network is supported by two aluminum trays spanning 60 feet that are attached to 11 steel angle brackets and anchored into the wall’s reinforced concrete beams using ½ inch steel bolts. The aluminum trays are located approximately 9 and 11 feet, respectively, above the floor of the lab, and can be accessed from the hydraulics laboratory’s sedimentation flume walkway.

The system is also equipped with a DATAQ data acquisition system consisting of 44 different sensors that monitor and record the pressure, flow, conductivity, and water level at various points in the system network. A more complete description of the system is presented in the *Physical Model Design and Construction Report*. A brief overview is presented:

Physical Components

Tanks

There are three tanks located approximately 17 feet above the laboratory floor. Each tank has a volume capacity of 110 gallons. These are used to simulate the actual operation of water storage tanks within a typical water utility system. If they are allowed to fill, they can pressurize and feed the system without the assistance of the pump. When studying particular dynamics or conditions of flow, it is generally useful to try and keep the system in a steady state condition. For steady state conditions ideally the system is not changing. This can generally be governed by keeping the tank levels constant, except in circumstances where the tanks are shut off completely.

Each tank also possesses an overflow line that will allow water to flow out of the tank and back into the reservoir. The overflow level in each tank is about 32 inches. This level however varies from tank to tank and was monitored carefully when collecting in order to avoid ambiguity about whether or not the tanks are overflowing.

Figure 40: Elevated storage tank

Reservoir

The reservoir is located against the back wall of the laboratory and underneath the far side of the pipe network. The construction was primarily of treated wood, bolts, and waterproof plastic liner. The reservoir can hold up to 900 gallons of water. It is not recommended to fill the reservoir to near full capacity because of the stress it places on the structure. The reservoir level was therefore generally maintained at about 1 foot from its full height (~5 ft.) when not in operation. While operating, this level should never drop below 1.5 feet in order to reduce the possibility of pump cavitation. The reservoir is fed via two collection lines that return water flowing out of the system from the various outlets so that the water volume is fully conserved. The procedures for draining the reservoir and correcting any leaks will be discussed later in the document.

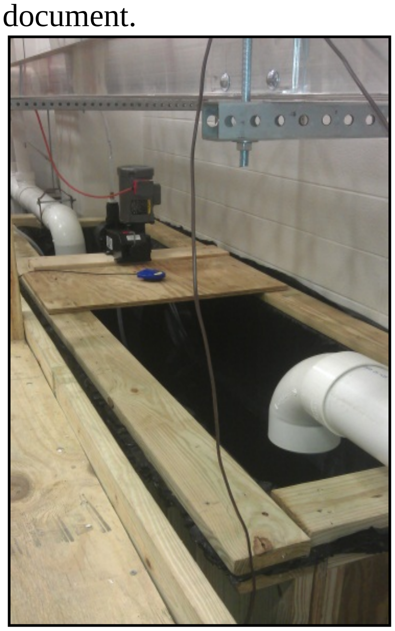

Figure 41: Reservoir

Pump

The pump used to run the system is a three horsepower Grundfos model CR 20-1. The pump has a rated flow of 102 GPM and a rated head of 52.8 feet. The pump is located on the ground adjacent to the reservoir and is connected by approximately 1.5 ft section of a 2 inch diameter PVC pipe. Downstream of the pump, there is a 2 inch brass gate valve that can be used to adjust the total amount of flow being fed into the system from the reservoir. There are also two tee joints that can be fitted with sensors or valves for injection or monitoring purposes.
Before proceeding with any experiment involving the system, it was critical to ensure that there is an outlet somewhere in the system that will allow the water to exit either back into the reservoir via the collection lines or into the tanks. This includes ensuring that the pump's gate valve is open far enough to let water pass through it to avoid damaging the pump.

Figure 42: Pump

Data Acquisition System

The data collection system consists of a series of sensors and meters that monitor pressure, flow, water levels and electrical conductivity. The instruments are discussed in greater detail in the design and construction report. All of these variables can be monitored and recorded through the LabView software installed on the computer located along the southern wall of the laboratory. All data from every experiment is automatically saved to a text file inside the Data Acquisition→data folder on the hard drive of the laboratory computer.

The data was collected using a program developed in LabView virtual instrument environment. The program allowed the experimental team to monitor any parameter of the system using time series plots and tables as the data was being collected and written to a text file. The collection phase in the program continually collects data and writes to the text output file. Thus a failure in the program during data collection leading to a crash does not destroy the data taken prior to that crash.

Figure 43: Tank level meter

Figure 44: Electrical conductivity meter

Ball Valves

These valves provide a simple means of opening and closing a segment of pipe. They are useful for establishing different conditions and flow patterns within the system, as well as rerouting water away from damaged or unwanted sections of the network. When operating these ball valves, it is best that no flow is going through the pipe being opened or closed in order to avoid creating water hammer effect.

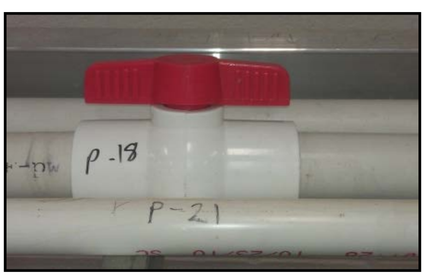

Figure 45: Ball valve

Gate Valves

The network was constructed with 10 different demand nodes and 3 tanks, each of which contains a flow meter and a gate valve. Each gate valve allows the user to adjust the amount of flow passing through a pipe, and hence, the amount of demand (or inflow in the case of the tanks) placed upon the system.

These valves are instrumental in establishing steady state scenarios as well as adjusting the overall dynamics of the system. The circumference of each valve has been demarcated into eighths in order to help quantify and repeat any adjustments made to the system. During the course of the experiments, the turn settings as the number of full turns and number of 1/8 turns from fully open was recorded in the experiment's notes.

Figure 46: Gate valve

Injection Check Valve

A check valve's basic functionality allows flow to proceed in one direction through it. The particular check valve in the model is used for injection experiments involving either a syringe or the Omni injection pump. If performing an injection with the syringe, the valve would be placed in the desired system position and fitted with a ¼ inch brass barb and ½ - ¼ inch bushing. When using the Omni pump, the bushing and barb would be replaced with the brass three-way valve. This three-way valve was equipped with two hoses; the vertical hose attached to the top provides the injecting fluid from the Omni pump while the other hose protruding from the side serves as the release. The purpose of this configuration is to get water all the way to the injection point prior to beginning the experiment so that the actual injection into the system and the collection of data can be as exactly as possible synchronized in time. This will be accomplished by directing the injecting fluid to the release hose first so that the fluid can fill the line completely and once redirected, can immediately begin feeding into the actual system.

Figure 47: Three-way valve and check valve

Injection Pump

One of the primary purposes of this research is to trace and study the flow of contaminants within a pipe network. The pump selected to inject conservative contaminants is an

Omni Mechanical Diaphragm Metering Pump, model DC5C2PP. This pump has been installed on the top of the reservoir and has the ability to pump approximately 1.45 GPM against a pressure of about 90 PSI. It operates using a reciprocating diaphragm that draws water in from a source (usually a bucket of contaminated water) with a "Suction Stroke" and pushes it out and into the system with the diaphragm arm striking the collection chamber on a "Discharge Stroke." The length and strength of the stroke can be adjusted according to how much injection is required for a particular experiment or how much residual pressure the pump is working to overcome in the system. As with the larger reservoir pump, this smaller pump should not be run without a minimum water height supplying the pump.

Figure 48: Injection pump

Injection Syringe

The syringe was designed and constructed within the lab to simply serve as a convenient means of studying general "plug" flow patterns and testing experimental setups and instruments. It consists of 2 separate pieces of PVC pipe with one serving as the shaft and the other as the plunger. The syringe is a very crude instrument and would not be used to perform any "official" experiments where the data will be analyzed. The protocol for proper use of this instrument will be discussed in the next section. The primary purpose of the syringe was to determine if each of the electrical conductivity meters were operating properly and reading the locally injected solution concentration.

Figure 49: Injection syringe

General Comments/Concerns

Working with the experimental physical model system revealed some issues with the instruments and required troubleshooting. Some of the more problematic issues are summarized below.

The conductivity meters have a tendency to trap air and give inconsistent and inaccurate measurements of the conductivity at those particular locations. This issue stems from the fact that meters are installed with their probes protruding vertically downward into the flow stream. This orientation is acceptable by the manufacturer's guidelines. However, the ideal orientation from the manufacturer's guidelines is horizontal in a tee with the flow proceeding opposite to the probe and flowing around in a 90 degree angle. This would not be practical installation for the design area of the network. The best solution in troubleshooting the issue was found to be to monitor which meters are reading lower than expected values and loosen their threaded connections enough to allow the trapped air to escape and prevent a region of trapped air building up around the probe. It is usually sufficient to perform this check once before collecting data for an experiment. However, the issue can persist and had to be monitored carefully when analyzing EC data for an experiment. There are 6 conductivity meters and 13 different monitoring positions and it was critical to note the location in experimental notes for each test using conductivity measurements.

The flow meters have minimum detectable flow rates depending upon the diameter of the meter. For example, the 1 inch flow meters located on the demand nodes cannot read below 0.80 GPM. Any data reflecting a flow of less than about 0.8 GPM consequently, is considered to be either inconclusive or zero. All the instruments being used for data collection have similar ranges of usability and have on-board settings to adjust them. It is necessary therefore to always be aware of what settings each instrument is operating under for a particular experiment and if the recorded average value is either near the lower limit or the upper limit of measurement. At either the lower or upper limit, the average may be biased from the true average by the variability on the upper limit or lower being dampened by the limit of measurement.

The specific flow meter utilized in the work is a unidirectional flow meter. Flow meters from the manufacturer are available that can measure flow direction but were not used for the research project. There can be some issues interpreting in some scenarios with the tank flow meters. This is only location where a flow reversal is able to occur in two different directions, during a steady state simulation.

At the 1 inch demand nodes if the system pressure is especially low, the meters may not be able to read the amount that is actually flowing out of a demand node. The flow meters operate by measuring the speed at which particles in the water return a transmitted signal to a transponder within the meter. A partial water surface may occur in the area around the gate valve and flow meter and bias the reading to a zero reading for gauge pressures near zero.

Procedural Outlines

In this section, a protocol for specific experiments and procedures will be detailed and discussed. The methods presented here have evolved directly from the experience and knowledge of the experimental team.

Basic Experimental Procedure

Here is an outline of what would generally be done prior to beginning any experiment involving the hydraulic pipe network.

1) Turn on data acquisition system. (Current should read below ~0.20 A while system is not in use)
2) Turn on computer.
3) Once Windows opens, click on LabView → Launch LabView → LabModel.vi. This should open up the system interface where you can monitor the various parameters within the system. (Note: Instruments take measurements every 2 seconds, but they are collected and displayed approximately every 10 seconds)
4) Make sure the reservoir is at adequate level for the experiment such that the pump will not create vortex as it drains water.
5) Adjust demand and tank valves to whatever settings are required by the experiment. Also make sure that ball valves are set to their desired position as it is not recommended to adjust these while the system is in operation.
6) Place conductivity meters and injection check valves in their appropriate positions, insuring to place stainless steel plugs wherever there is an empty monitoring position.
7) Final Step: Turn on pump by at the circuit breaker circuit. If the pump runs without flowing water, it should be turned off before determining the cause of the issue.

Draining Reservoir Procedure

In the event that the reservoir becomes overly contaminated or is in need of maintenance, such as finding and correcting leaks, there is a simple method for draining it. This process should begin the evening prior to whenever the user intends to use the system next as it takes several hours to completely drain.

1) Connect one end of regular garden hose to faucet on southern laboratory wall and submerge the other end in the water reservoir.
2) Turn on hose, wait just a few seconds and then turn it off.
3) Immediately disconnect the hose from the wall faucet and place it where it can drain into the laboratory reservoir while allowing the other end of the hose to reach all the way to the bottom of the wooden reservoir.

Procedure for Establishing a Steady State

Steady state conditions are often the most advantageous for analyzing flow dynamics and patterns, so they were used in typical research experiments involving the hydraulic system. There are a multitude of different steady state scenarios that can involve one, two, or three tanks or none at all. The best and easiest way to produce steady state conditions proceeds as follows.

1) Determine the pipe configuration that is most desired for the experiment (which ball valves to turn on/off) and what tanks should be used.
2) Refer to the procedural section for "Before you Begin…." and follow the steps outlined there.
3) Send one person up to the flume with a radio device (e.g. walkie talkie) to operate valves while a partner remains at the monitoring station (computer) with a second radio.
4) Shut off all (or most) demand valves in order to allow tank(s) to fill. (It is much easier to regulate and steady the tanks levels while they are draining instead of filling)
5) Once tank(s) are overflowing, begin opening the desired valves according to previously determined experimental objectives and global system sensitivity.

   NOTE: Global system sensitivity refers to the fact that some demand valves affect the global flow pattern of the system more than others, and hence, have a greater impact on the flows coming in and out of the tanks. As a general rule, demand nodes that are located closer to the pump (i.e. J-4071 and J-4069) will have a greater effect on the flows throughout the system as they are receiving the strongest amount of flow and thereby release the most when opened.

6) Use the monitoring charts and tables in the LabView program to see how tank levels respond to the opening and closing of various valves. Then proceed to make any adjustments needed to stabilize or at least slow down the change of water levels in the tanks. These adjustments are most easily communicated and quantified through fractions of a turn, as the valves are already marked according to eighth turns.
7) Once tank flows have slowed down to the point where their readings are at or below their tolerance levels, continue to monitor the tanks' water levels until experimenter is satisfied that the system characteristics and flow pattern are steady and consistent enough for the purposes of the experiment.
8) Stop the LabView model and restart the LabView model. Save the text files with the pre steady state and steady state file folder.

Procedure for Injection Using Syringe

This procedure was intended to provide an easy way to test how a conservative contaminant plug might flow through the system and troubleshoot instruments. It requires a supply of Calcium Chloride Dihydrate ($CaCl_2 \cdot 2H_2O$), which is 75.5% $CaCl_2$ salt by weight, and a large plastic syringe. It also requires 2-3 persons (ideally), 2-3 radios, a stopwatch, a Quick Grip clamp, and a liter-sized graduated cylinder.

1) Attain the appropriate or desired settings for the particular experiment according to the procedures for "Before you Begin…" and "Establishing a Steady State."
2) While system is becoming steady, measure out about 2.1 grams of $CaCl_2$ using a scale and mix it into one liter of water from the tap using the large plastic graduated cylinder.

NOTE: Salt is actually Calcium Chloride Dihydrate ($CaCl_2 \cdot 2H_2O$). Since $CaCl_2$ is about 75.5% of the salt by mass, the solution concentration will be approximately 1.6 g/L.

3) Once properly mixed and system has reached its appropriate state, send two persons with two radio devices, the syringe, the solution, a Quick Grip clamp and a stopwatch to the injection point and leave one at the computer with a third radio to monitor and record data.
4) Attach the hose at the bottom of the syringe to the injection barb sticking up out of the injection valve.
5) Have one person steady the syringe in a vertical inclination while his or her partner pours the entirety of solution into syringe shaft through a funnel.
6) Once the person that has poured the solution into shaft, he or she should slide the plunger into the syringe shaft until it just makes contact with the surface of the solution. Now, all three individuals should be ready to proceed with injection.
7) Have the person at the computer countdown to injection over the radio. Once he or she says “GO,” one person will begin injecting solution by pushing down on the plunger, his or her partner will begin timing them with the stopwatch while still helping to steady the syringe and the third experimenter will begin recording data by clicking on the white arrow on the top left hand side of monitoring interface. All three actions must be synchronized as best as possible for the sake of accuracy.
8) Once the injection is complete, stop the stopwatch, clamp the hose on the syringe and remove it from the injection barb.
9) Continue to monitor conductivity meters until experimenters are satisfied with the amount of data collected.
10) Once satisfied, stop recording by clicking on the red circle near the top left hand side of the monitoring interface.
11) Record the duration of injection and measure the amount of solution still remaining in the syringe using the graduated cylinder. Subtract this volume from the initial injection amount (one liter) to get the total amount of contaminant injected.
12) Create a text file describing the experiment, participants and system conditions (number of turns on each valve, water levels, conductivity meter positions, etc.). Also record the amount of injected solution, the time it took and the injection flow rate (= volume/time).
13) Save this file in the same place as the actual experimental data.

Injection using Omni Pump

This procedure describes the appropriate method and steps involved in performing an actual injection experiment. This procedure involves the Omni injection pump, the injection check valve with three-way lever, a supply of $CaCl_2$, a liter-sized graduated cylinder, at least two 5 gallon buckets, stopwatch, 2-3 radios, 2-3 persons, and two stoppers or clamps for pump hoses.

1) Attain the appropriate or desired settings for your particular experiment according to the procedures for “Before you Begin…” and “Establishing a Steady State.”
2) While the system is stabilizing to a steady state, measure out the appropriate amount of $CaCl_2$ required for this experiment understanding that injections using the pump typically require concentrations of only about 0.755 g/L $CaCl_2$ (1 g/L salt).
3) Mix salt with the desired amount of water and pour into buckets.

4) Take one empty bucket to the injection point and the one(s) filled with $CaCl_2$ solution to Omni point.
5) Have one person located at the Omni pump, one person at the injection point with a stopwatch, and the third member stationed at the computer, all with radios.
6) Configure the three-way injection valve such that any flow is directed through the release hose and into the empty bucket.
7) Submerge the Omni pump's inlet hose into one of the buckets of solution.
8) The person at the pump can turn it on by plugging the pump's power cord into a power source or by turning on the power strip that it is already plugged into.

   NOTE: If there is not water already in the line, the person operating the pump may need to increase its power or stroke length in order to initially get the solution to flow.

9) Once the solution reaches the release bucket and its flow becomes relatively steady, the person operating the pump may readjust the stroke length back to its desired level if needed.
10) Once ready, the person at the injection valve can countdown via the radio and start their stopwatch at the same time they turn the three-way lever from release to injection while the person at the computer begins collecting data.
11) Continue injecting until experimenters are satisfied or the solution runs out.
12) Once experimenters are ready to finish, they can turn off the pump, switch the three-way lever to the release position and stop the stopwatch.

At this point, they are two options on how to proceed. The first option is to detach the pump hose from the injection valve. Any remaining fluid drains from the line into the release bucket so they can measure the amount of fluid remaining in the line and repeat experiment exactly as above.

Another option for if the experiment will be repeated with the same concentration, is the pump and lever switch can be shut off. Following that immediately clamp or plug the ends of the hoses and keep whatever fluid still remains in the line. At capacity, this amount should be approximately 1.2 liters. The next time an injection is performed, the pump power can be adjusted to initialize flow or have to wait as long for the flow to become steady. However, the subsequent experiment will have to add this volume to their initial injection amount.

13) Measure the amount of fluid in the release bucket and add to that any amount of fluid that still remains in the pump line.
14) Subtract this volume from the initial injection amount to find the total amount of injected material and divide it by the length of injection time to get the flow rate.
15) Continue to monitor conductivity meters until experimenters are satisfied with the amount of data collected, and once satisfied, stop recording by clicking on the red circle near the top left hand side of the monitoring interface.
16) Create text file describing the experiment, participants and system conditions (number of turns on each valve, water levels, conductivity meter positions, etc.). Also record the amount of injected solution, the time it took and the injection flow rate.
17) Save this file in the same place as the actual experimental data.

Appendix B: Flow Discrepancy Data

Table 27: Flow discrepancy data

6/25/2012 KYPIPE comparisons of experimental to modeled pressure for dif flow measures					
J-4069 & J-4071 fully open & pump gate valve 7 turns from fully open					
Model description	**Pump outlet**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	23.79	7.62	7.22		
Model pressures (using outlet flow meters)	24.16	7.6	7.23	100.47%	12.5
Model pressures (using transmission flow meters)	24.81	7.63	7.2	101.37%	15.8
Model pressures (using adj flows to correct flow discrepency)	24.48	7.62	7.22	100.96%	14.1
Model pressures (using handheld flow meters)	25.59	7.84	7.07	102.79%	20.5

J-4069 & J-4071 1 turn from fully open & pump gate valve 7 turns from fully open					
Model description	**Pump outlet**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	23.79	7.62	7.22		
Model pressures (using outlet flow meters)	24.28	7.71	7.26	101.26%	13
Model pressures (using transmission flow meters)	24.93	7.67	7.17	101.58%	16.5
Model pressures (using adj flows to correct flow discrepency)	24.61	7.66	7.18	101.13%	14.8
Model pressures (using handheld flow meters)	25.91	7.61	7.23	102.97%	22.8

J-4069 & J-4071 2 turns from fully open & pump gate valve 7 turns from fully open					
Model description	**Pump outlet**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	24.59	9.75	9.11		
Model pressures (using outlet flow meters)	25.04	9.75	9.17	100.85%	12.8
Model pressures (using transmission flow meters)	25.6	9.71	9.1	101.21%	16.1
Model pressures (using adj flows to correct flow discrepency)	25.33	9.7	9.1	100.81%	14.5
Model pressures (using handheld flow meters)	27.47	9.75	9.1	103.89%	31.4

J-4069 & J-4071 3 turns from fully open & pump gate valve 7 turns from fully open					
Model description	**Pump outlet**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	26.75	15.41	14.85		
Model pressures (using outlet flow meters)	27.69	15.98	15.42	103.68%	13
Model pressures (using transmission flow meters)	28.04	15.95	15.4	104.00%	16.1
Model pressures (using adj flows to correct flow discrepency)	27.67	15.97	15.42	103.63%	14.5
Model pressures (using handheld flow meters)	30.46	15.31	15.14	105.05%	60

J-4069 & J-4071 4 turns from fully open & pump gate valve 7 turns from fully open					
Model description	**Pump outlet**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	29.83	23.95	23.50		
Model pressures (using outlet flow meters)	32.13	25.66	25.93	108.39%	13
Model pressures (using transmission flow meters)	32.2	25.62	25.89	108.36%	16.1
Model pressures (using adj flows to correct flow discrepency)	32.17	25.64	25.91	108.38%	14.5
Model pressures (using handheld flow meters)	32.8	25.49	25.55	108.36%	60

J-4069 & J-4071 5 turns from fully open & pump gate valve 7 turns from fully open					
Model description	**Pump outlet**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	32.35	27.80	27.92		
Model pressures (using outlet flow meters)	33.7	29.05	29.04	104.22%	13
Model pressures (using transmission flow meters)	33.64	28.97	28.97	103.98%	16.1
Model pressures (using adj flows to correct flow discrepency)	33.64	28.99	28.98	104.02%	14.5
Model pressures (using handheld flow meters)	33.72	29.04	29.03	104.22%	60

6/29/2012 KYPIPE comparisons of experimental to modeled pressure for dif flow measures						
J-4069 & J-4071 fully open & pump gate valve 7 turns from fully open						
Model description	**J-4090**	**Pump**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	17.22	23.36	7.38	7.03		
Model pressures (using outlet flow meters)	17.14	23.79	7.54	7.05	100.96%	12.8
Model pressures (using transmission flow meters)	17.24	24.41	7.94	7.63	105.19%	15
Model pressures (using adj flows to correct flow discrepency)	17.24	24.41	7.79	7.39	103.83%	13.8
Model pressures (using handheld flow meters)	17.26	22.45	6.78	6.45	95.00%	8.4

J-4069 & J-4071 1 turn from fully open & pump gate valve 7 turns from fully open						
Model description	**J-4090**	**Pump**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	17.22	23.36	7.38	7.03		
Model pressures (using outlet flow meters)	17.14	23.79	7.54	7.05	100.96%	12.8
Model pressures (using transmission flow meters)	17.21	24.49	8.01	7.59	105.33%	15.4
Model pressures (using adj flows to correct flow discrepency)	17.27	24.23	7.94	7.46	104.44%	14.2
Model pressures (using handheld flow meters)	17.24	22.77	6.86	6.69	96.43%	9.3

J-4069 & J-4071 2 turns from fully open & pump gate valve 7 turns from fully open						
Model description	**J-4090**	**Pump**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	18.69	24.13	9.41	9.01		
Model pressures (using outlet flow meters)	18.8	24.72	9.79	9.27	102.48%	12.8
Model pressures (using transmission flow meters)	18.79	25.21	9.99	9.64	104.53%	15
Model pressures (using adj flows to correct flow discrepency)	18.84	24.97	9.93	9.5	103.80%	13.8
Model pressures (using handheld flow meters)	18.66	23.94	9.05	8.78	98.15%	10.2

J-4069 & J-4071 3 turns from fully open & pump gate valve 7 turns from fully open						
Model description	**J-4090**	**Pump**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	22.69	26.17	14.98	14.48		
Model pressures (using outlet flow meters)	23.29	27.24	15.79	15.24	104.33%	12.8
Model pressures (using transmission flow meters)	23.24	27.56	15.88	15.41	105.03%	15
Model pressures (using adj flows to correct flow discrepency)	23.29	27.4	15.86	15.35	104.79%	13.8
Model pressures (using handheld flow meters)	22.73	28.39	15.56	15.7	105.23%	24

J-4069 & J-4071 4 turns from fully open & pump gate valve 7 turns from fully open						
Model description	**J-4090**	**Pump**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	28.64	29.14	23.30	22.96		
Model pressures (using outlet flow meters)	30.58	31.53	25.38	25.08	108.30%	12.8
Model pressures (using transmission flow meters)	30.57	31.61	25.4	25.12	108.42%	15
Model pressures (using adj flows to correct flow discrepency)	30.59	31.57	25.4	25.11	108.39%	13.8
Model pressures (using handheld flow meters)	30.31	32.4	25.51	25.32	109.21%	75

J-4069 & J-4071 5 turns from fully open & pump gate valve 7 turns from fully open						
Model description	**J-4090**	**Pump**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	31.87	31.60	27.18	27.11		
Model pressures (using outlet flow meters)	33.01	33.1	28.45	28.43	104.47%	12.8
Model pressures (using transmission flow meters)	33	33.1	28.44	28.43	104.45%	15
Model pressures (using adj flows to correct flow discrepency)	33.01	33.1	28.44	28.43	104.46%	13.8
Model pressures (using handheld flow meters)	33.03	33.1	28.46	28.47	104.53%	13.8

7/02/2012 KYPIPE comparisons of experimental to modeled pressure for dif flow measures						
J-4069 & J-4071 fully open & pump gate valve fully open						
Model description	**J-4090**	**Pump**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	19.97	21.63	9.15	8.70		
Model pressures (using outlet flow meters)	19.96	22.1	9.37	8.81	101.44%	3
Model pressures (using transmission flow meters)	19.94	22.78	9.67	9.31	104.45%	4.5
Model pressures (using adj flows to correct flow discrepency)	19.93	22.46	9.5	9.04	102.83%	3.8
Model pressures (using handheld flow meters)	19.56	20.09	7.73	7.14	89.33%	0.2

J-4069 & J-4071 1 turn from fully open & pump gate valve fully open						
Model description	**J-4090**	**Pump**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	20.53	22.22	9.74	9.16		
Model pressures (using outlet flow meters)	20.41	22.56	9.83	9.2	100.57%	3
Model pressures (using transmission flow meters)	20.57	23.37	10.41	9.93	105.16%	4.5
Model pressures (using adj flows to correct flow discrepency)	20.46	22.98	10.1	9.54	102.73%	3.8
Model pressures (using handheld flow meters)	20.86	22.83	10.68	9.55	104.56%	2.8

J-4069 & J-4071 2 turns from fully open & pump gate valve fully open						
Model description	**J-4090**	**Pump**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	21.82	23.33	11.75	11.16		
Model pressures (using outlet flow meters)	21.83	23.73	11.98	11.33	101.32%	3
Model pressures (using transmission flow meters)	22.01	24.48	12.58	12	105.11%	4.5
Model pressures (using adj flows to correct flow discrepency)	21.9	24.12	12.26	11.65	103.13%	3.8
Model pressures (using handheld flow meters)	21.94	24.43	12.8	11.54	104.41%	4.5

J-4069 & J-4071 3 turns from fully open & pump gate valve fully open						
Model description	**J-4090**	**Pump**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	25.24	26.18	17.14	16.55		
Model pressures (using outlet flow meters)	25.79	27.01	17.88	17.29	103.53%	3
Model pressures (using transmission flow meters)	25.87	27.47	18.22	17.65	105.09%	4.5
Model pressures (using adj flows to correct flow discrepency)	25.81	27.25	18.04	17.46	104.27%	3.8
Model pressures (using handheld flow meters)	25.18	29.46	18.9	17.87	107.63%	21

J-4069 & J-4071 4 turns from fully open & pump gate valve fully open						
Model description	**J-4090**	**Pump**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	29.65	29.61	24.29	23.90		
Model pressures (using outlet flow meters)	31.67	31.98	26.77	26.86	109.36%	3
Model pressures (using transmission flow meters)	31.67	32.06	26.5	26.17	108.42%	4.5
Model pressures (using adj flows to correct flow discrepency)	31.66	32.02	26.48	26.14	108.33%	3.8
Model pressures (using handheld flow meters)	33.2	33.28	28.63	28.23	115.09%	0.2

J-4069 & J-4071 5 turns from fully open & pump gate valve fully open						
Model description	**J-4090**	**Pump**	**J-4069**	**J-4071**	**Average pressure difference**	**K value for partial gate valve closure**
Measured pressure	32.42	32.12	27.70	27.70		
Model pressures (using outlet flow meters)	33.51	33.59	28.95	28.94	104.23%	3
Model pressures (using transmission flow meters)	33.51	33.59	28.94	28.93	104.21%	4.5
Model pressures (using adj flows to correct flow discrepency)	33.51	33.59	28.95	28.94	104.23%	3.8
Model pressures (using handheld flow meters)	33.51	33.59	28.95	28.94	104.23%	0.2

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