Water Distribution System Real-Time Network Model Evaluation: Summary of Available SCADA and Tracer Test Data

Developed by the University of Cincinnati

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Contents

1 Introduction

This report summarizes and describes the data that will be used to develop and evaluate a real-time hydraulic and water quality model of theNorthern Kentucky Water District (NKWD) water distribution system. These data include both those routinely collected through the District's Supervisory Control And Data Acquisition (SCADA) system, as well as labor intensive field test data from injecting and tracking a salt tracer in a large section of the distribution system during November, 2012.

SCADA systems are routinely employed in water utilities of all sizes, primarily to remotely monitor and control treatment processes, but also to remotely monitor and control distribution system hydraulic operations. It is the distribution system and source boundary measurements that are of interest for real-time modeling. Broadly, these measurements monitor treatment plant clearwell and distribution system storage levels, high service and booster pump runtime statuses, pump station suction and discharge pressures and flow rates, upstream and downstream pressures at key regulating valves, and various other flow and pressure measurements that are valued by the utility for monitoring the status of their distribution system operations. Some of these measurements are essential, and all of them are useful, for real-time hydraulic and water quality modeling in the distribution system. It would be impossible, for example, to develop an accurate real-time hydraulic model without being able to accurately assess and set the statuses of pumps in real-time, as those discrete statuses have a strong impact on the distribution and magnitude of flows within the pipeline network. Other measurements, such as pump station flows and storage water levels, are critical to real time modeling in a less direct way; they are used to construct flow balances within demand management areas, and thus calculate the modeled water demand within such areas in real-time. SCADA systems routinely collect other information related to treatment process operation and chemical dosing, and water quality measures at key points of the distribution system. These measurements are not considered here, however, as they are not directly used for purposes of building real-time hydraulic models. Distribution system water quality measures collected in SCADA could potentially be used for real-time water quality modeling, but we do not consider them here because the real time water quality models will be limited to predicting the movement of a salt tracer, rather than being used to predict more general water quality indicators that would be recorded in SCADA, such as free chlorine residuals.

Salt tracer tests have been conducted in several large scale systems over the past decade without any known adverse incident. Members of the study team designed and conducted the first known large scale salt tracer test in the distribution system of Hillsborough County (FL) Water Department, and participated in several salt tracer studies with the Greater Cincinnati Water Works. The former used a sodium chloride tracer solution, while the latter used calcium chloride, as used in the present study. These studies provided highly accurate data that were very informative for illustrating travel paths and residence times in the distribution system, and thus for rigorously evaluating the accuracy of a real-time water quality model.

The field experiment described here is one of only a few distribution system water quality studies that attempted to follow a large volume of finished water through an extensive portion of the distribution system. Such data provide unique information about processes that affect water quality in the distribution system, including flow path-dependent effects, and will be valuable for evaluating the real-time network hydraulic and water quality models. Data collected will be used to assess the accuracy of real-time model predictions and forecasts, and to refine the real-time model assumptions.

2 SCADA Data Description

In general, it would be rare that information from a raw SCADA data stream would be attached to a real-time model. Raw SCADA data typically require resampling, filtering, and other data transformations in order to allow them to be reliably used as real-time model boundary conditions or settings. Even SCADA data used purely as measurements for comparison purposes should often be resampled and filtered, to reduce noise and focus on the comparison with the true signal. Here, however, the purpose is to describe the types of SCADA data streams that will be used to derive input to a real-time network model for the NKWD case study. A later document will describe in detail the transformations performed in order to render these data streams acceptable for real-time modeling.

Table 1 summarizes the categories of SCADA data streams used for the real-time model, as well as a coarse categorization of how those data streams will be used, and the number of data streams in each category. It should be noted first that the 164 data streams processed for real time modeling represent a small fraction of the total number of SCADA tags recorded in the SCADA historian database. The SCADA Category summarizes briefly the type of data contained in the database. Generally, these SCADA streams measure flow rates, water levels, accumulated times (as in a pump runtime meter), or pressures.

The second column listing the Parameter Type describes the real-time model parameter that will ultimately be represented by the SCADA data stream. Again, none of these streams will be directly connected to real-time model elements without significant data processing, but the Parameter Type gives information about the reason why each SCADA stream is included. Each parameter type is either a "Boundary" or a "Measure." Boundary parameters represent exogenous factors that directly set model elements. Thus a Flow Boundary represents a time varying specified flow boundary condition – either a known demand or supply. A Head Boundary represents a specified head boundary condition, Status boundary parameters relate to pipe, valve, and pump open/closed status, and Setting boundary parameters represent valve settings that are fractional such as the percent open of an isolation valve, or the pressure setting of a PRV. Measure parameters are valuable SCADA streams

Table 1: Summary of SCADA data streams used for real-time modeling

SCADA Category	Parameter Type	Model Element	Quantity
Master Meter Flow	Flow Boundary	Node	6
Clearwell Level	Head Boundary	Reservoir	4
Pump Runtime	Status Boundary	Pump	43
PRV/Meter Pit Pressure	Setting Boundary	PRV	8
Plant Filter Discharge	–	–	33
Plant/PRV Discharge	Flow Measure	Pipe	7
Pump/Station Discharge	Flow Measure	Pipe	15
Pump/Station Suction Pressure	Pressure Measure	Node	11
Pump/Station Discharge Pressure	Pressure Measure	Node	17
Storage Tank Level	Level Measure	Tank	20
Total	–	–	164

that represent calibration data for comparing to real time model predictions; these measures do not, however, directly affect the real-time simulation.

Two SCADA categories deserve further explanation. The Plant Filter Discharge data streams are listed without a parameter type or model element, because those data streams enter into flow balances around treatment plant clearwells (they represent the inflow terms), with the result of those calculations being the flow out of the clearwell, or the distribution system supply flows. Separate flow measures already measure the plant discharges, but it was decided to construct the clearwell volume balances to use as an independent check on these critical supply flows. Thus, the Filter Discharge data streams would not be strictly needed in this application, but were useful as redundant measures on the supply flow rates for each of the three treatment plants.

The Storage Tank Level and Plant/Pump Discharge data streams are used for dual purposes as measure parameters and as boundary parameters – the latter through their participation in the calculation of real-time model demands. Real-time model demands are calculated via flow balance on network demand management zones delineated by boundary flow measures and closed pipes. The boundary flows are obtained from the flow measure parameters, and so those data streams are used both as measure parameters and indirectly to set real-time water demands. Similarly, the flows contributed to a zone from storage are computed indirectly from the level measures, and so those data streams also serve dual purposes as measures and demand (boundary) parameters.

2.1 SCADA data stream examples

The research team has exhaustively reviewed all SCADA data streams for visually obvious anomalies. Where obvious anomalies were present - including data gaps or unusual noise characteristics - strategies were developed for addressing them through the data transformation process. These data transformations will be detailed in a subsequent report on real-time model results. Here, we focus on illustrating the various SCADA data streams that are used for real-time network modeling, so that the reader has the benefit of visualizing typical data streams, and noting some of the more common issues that must be dealt with when using raw SCADA data. While it is impractical, and likely not helpful, to visualize all 164 SCADA data streams, we can visualize selected data within the different SCADA categories.

Figure **??** shows typical raw tank level data. These data must be converted into tank inflow for purposes of demand estimation, and are also used as level measures for comparison with real time model predictions. There is obvious noise present in the level data, including spikes of several feet usually associated with changes in pump status and consequent change from fill to drain cycle, or vice-versa. The low level noise can be dealt with easily by filtering, and filters must also manage the large spike increases/decreases. These large spikes, as well as the low level noise, are due to measuring tank level using pressure transducers that are located within the inlet/outlet line, and not on a static pressure line or within the tank itself. Thus the tank levels are affected by minor losses associated with tank piping and valving. When the tank is filling the hydraulic grade is an overestimate of the actual level, and when the tank is filling, it is an underestimate of actual level, due to the minor losses that occur between the transducer and the discharge point within the tank.

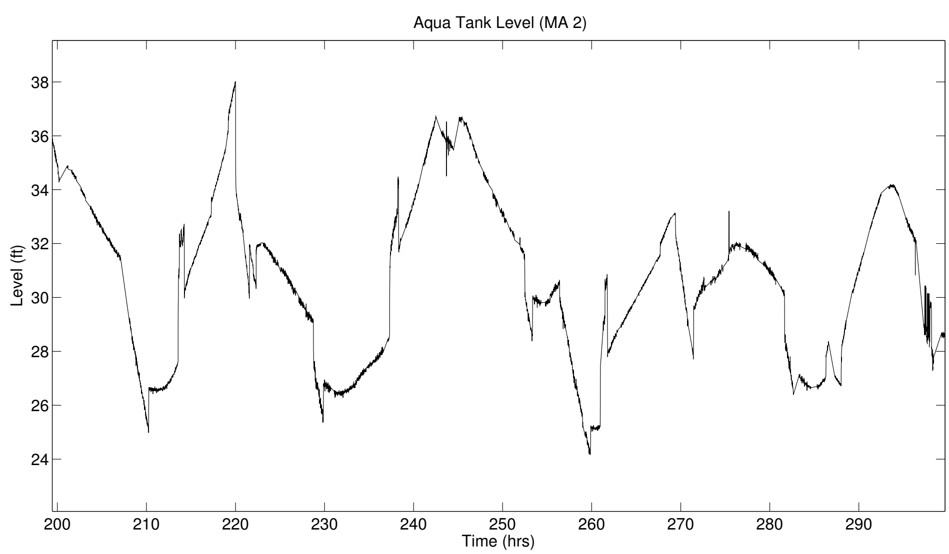

Figure 1: Typical raw storage tank water level data. Note signal noise and spikes separating fill and drain cycles.

Figure **??** shows raw pump station flow data at one of the more problematic flow measurement sites. The figure also shows calculated pump statuses at the same pump station, to aid in seeing when the pumps are on and thus when the flow through the station should be non-zero. Clearly there is a low level of noise occurring when the pumps are on and the flow is registering approximately 700 gpm. Troublesome, however, are the large gaps that seem associated with the pump off periods. These will be a problem if using these flow data for calculating demand within the zone receiving the pump station supply. If the data are resampled or interpolated, the flow when the pump is off – which should be zero for this pump station – will be significantly greater than zero, and produce a flow balance with significant errors. Strategies will need to be developed for trimming these flows so that the data gaps are managed effectively in real time. It is worth noting that such problems could conceivably be dealt with manually using a variety of methods, but in real time the data processing must be automatic and robust.

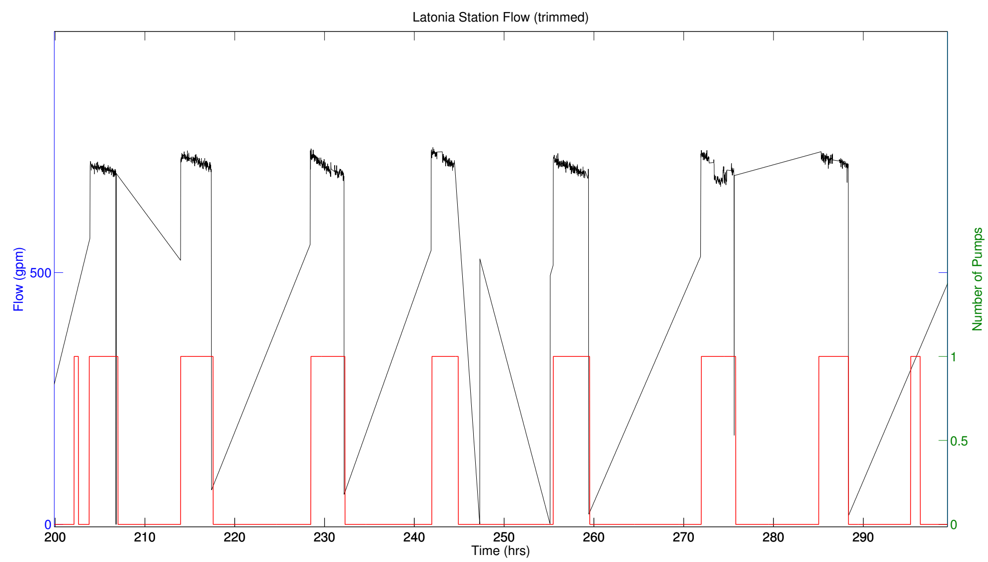

Figure 2: Raw pump station flow SCADA data and processed pump status showing large data gaps. Note that between pump on cycles flow data gaps are typically present, necessitating strategies for intelligently replacing these missing data.

Figure 3 shows the non-reset runtime for a typical high service pump. A non-reset runtime data stream has units of time, and increases by one second whenever the pump has been running for one second. Thus it is literally an hour meter showing how many hours the pump has run since the clock was zeroed. These data streams are critical for understanding the real-time status of high service and booster pumps, and must be processed in real time to derive binary pump statuses that will drive pumps in the real-time simulations. In this particular example, there are two pump on periods when the runtime slope is 1:1.

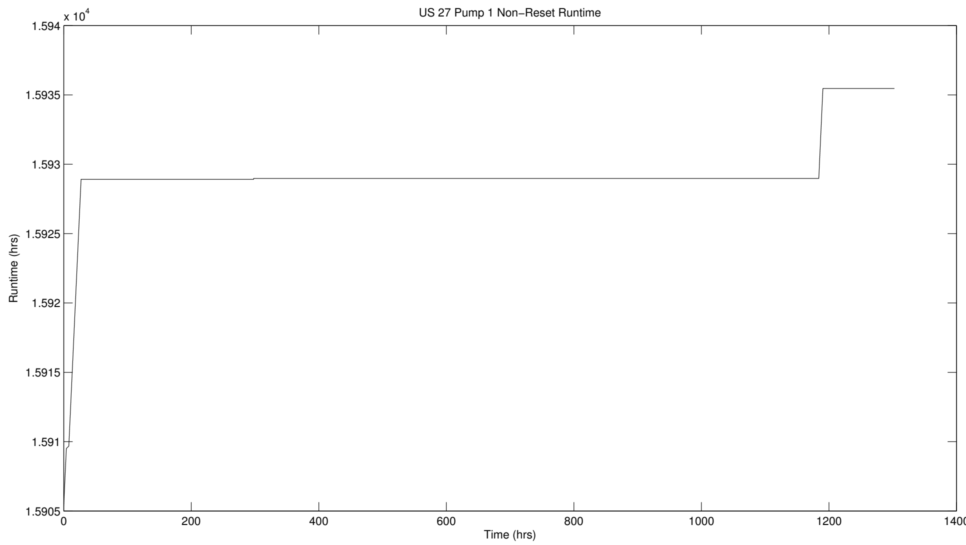

Figure 3: Raw pump non-reset runtime SCADA data. Pump status must be derived in real time from these data; pump is on when runtime is increasing 1:1 with clock time.

Figure 4 shows typical pressure measurement data – in this case the discharge pressure at a pump station. The signal is noisy and spiky, but that is typical and expected for such pressure data. The spikes will be correlated with hydraulic events occurring in the system, in particular with the start and stop of pumps at the pump station. Here, the data transformation would seek to smooth out the low level noise without eliminating the sudden spikes, which have real causes.

3 Tracer Field Study Area Description

Northern Kentucky Water District (NKWD) serves approximately 81,000 customer accounts, or nearly 300,000 people in Campbell and Kenton Counties, portions of Boone, Grant and Pendleton Counties, and the Greater Cincinnati Northern Kentucky International Airport. It covers over 300 mi^2 of total service area with the length of 1,282 miles of main pipes. The three water treatment plants: Fort Thomas Treatment Plant (FTTP), Taylor Mill Treatment Plant (TMTP), and Memorial Parkway Treatment Plant (MPTP), have a combined capacity of 64 Million Gallons Per Day (MGD), and supply water through 16 pump stations. The NKWD distribution system has 20 water storage tanks. A overview topography map of the study area is shown in figure 5. Red circle pins indicate conductivity monitor locations used in the field tracer test. The area is divided into six areas for convenience A to F which is

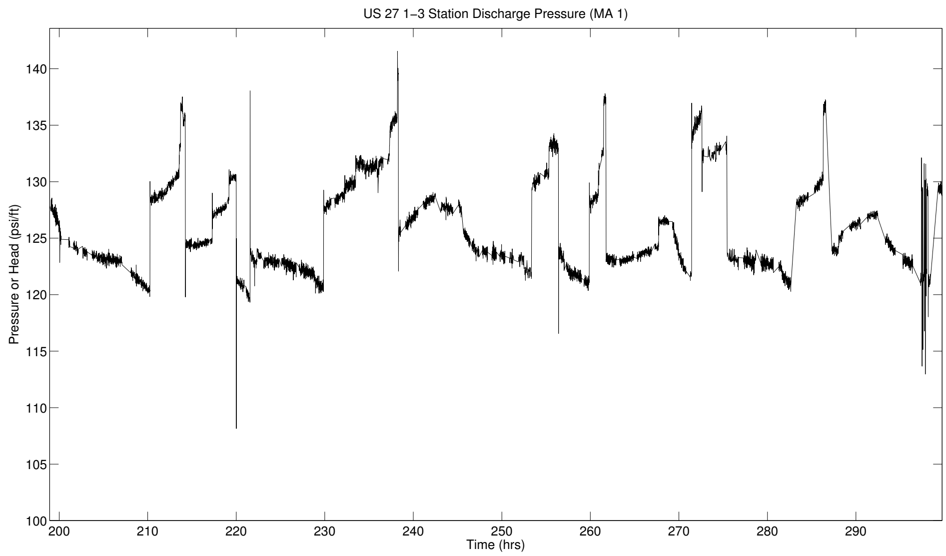

Figure 4: Raw pump station discharge pressure. Noise level is typical of most pressure data. Note the presence of cycles of intense data polling activity followed by data gaps. This behavior is seen in many raw SCADA time series but is unexplained.

followed as the name of area in northern Kentucky. Each area contains about 10 monitors.

The tracer experiments included a calcium chloride tracer test applied as a series of four pulses over a 12 hour period. The $CaCl_2$ pulses were used with 47 continuous conductivity meters to provide flow and velocity information at unusually high spatial and temporal resolution. The continuous specific conductance data shows that the injection pulses had a specific conductance more than twice the background level, though control on the target specific conductance level of 1,000 μS/cm was maintained throughout, and the peak increase was somewhat less than the design value. The four tracer pulses are clearly identified and were not significantly attenuated at some stations, whereas at stations involving more complex flow paths the original pulse signatures were not clearly identifiable. The tracer signatures – and in particular their degradation – still carry valuable information about the dynamics of the complex flow paths, flow rates, and travel times in the distribution system, and thus are very useful for calibrating and validating real-time water distribution system models.

Northern Kentucky Water District Figure 6 shows the water distribution network for the entire NKWD service area. The study area is represented as the blue colored network. The area is mainly supplied from the FTTP water treatment plant (WTP). A portion of the northern part of the service area could be served by both the MPTP and FTTP WTPs. The locations of WTPs are represented as brown rectangles on the map in figure 6. This area

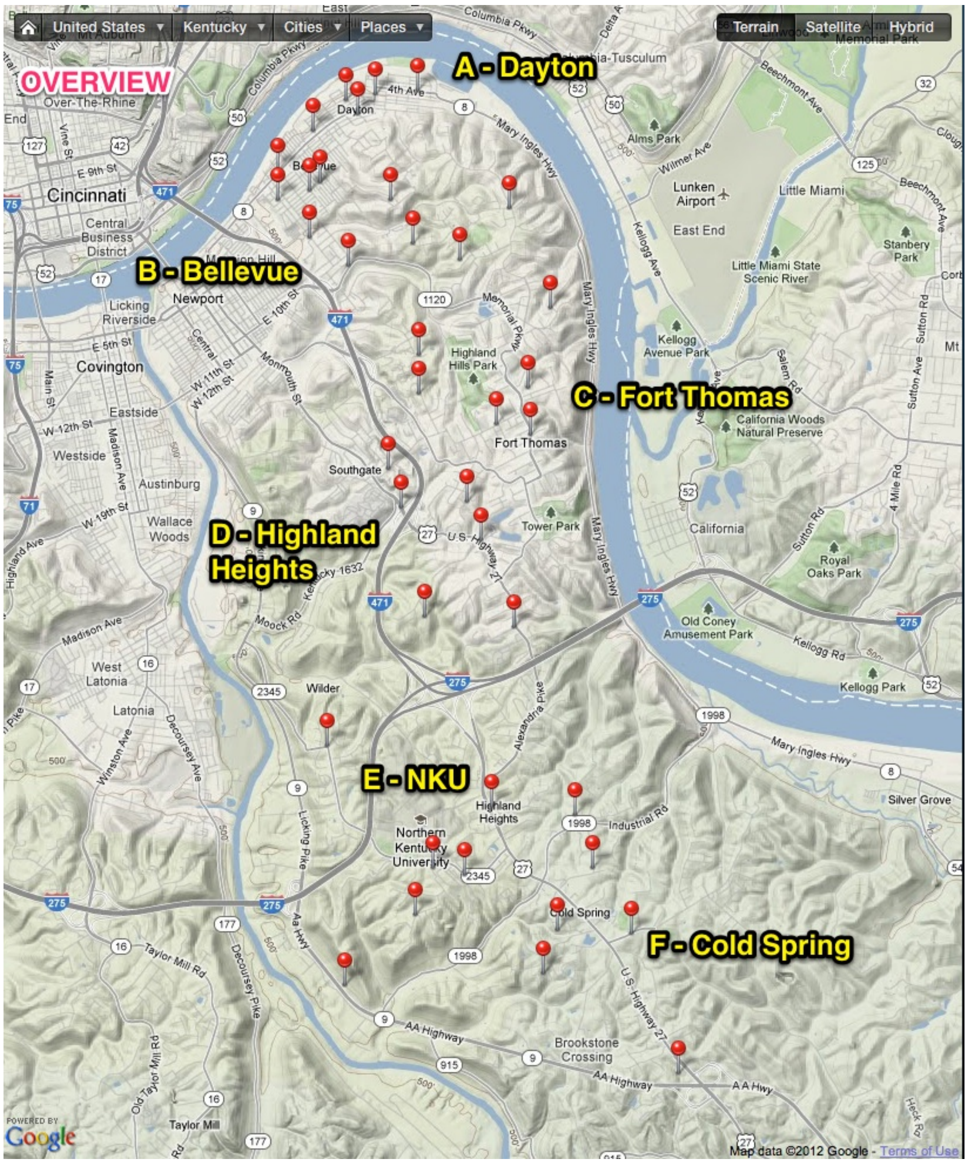

Figure 5: Overall sampling locations (red circle pins) on the topographic map in target area. Tracer monitor stations are located on each red circle pin spreaded to location A to F.

includes 1 pump station (US27) and 6 tanks which are not represented on the map. US27 pump station is located just outside of FTTP and distributes effluent water from the FTTP clearwells. The injection site was located at US27 pump station which is a distribution pump station of FTTP. US27 has 6 pumps with 2 main outlet pipelines, one is for north area supply and the other is for south area supply. 3 pumps distribute water in each direction.

Figure 6 also shows the pipe size distribution with thickness.

Distribution system flow paths begin at the single treatment plant source (FTTP), and continue through two main transmission lines (north and south), leading to 5 residential/commercial districts (areas A to F). Flow paths continue through area A to feed area B. Flow path splitting and recombination through areas A and B contribute to a progressively more complex set of contributing flow paths, compared to locations C and F.

All sampling locations were located in the field at fire hydrants using standard hydrant adaptors, and a continuous flow rate of approximately 1.0 GPM was maintained to reduce residence time in the hydrant barrel. Each sampling location was monitored by a continuous conductivity housed in a security box and containing a grab sampling port (see Figure 9 and Figure 10). Specific conductance data were downloaded from the continuous loggers periodically. The discharge line from each hydrant was positioned to ensure that it drained to a sewer (if present) or to an area that allows infiltration. The discharge from all hydrants will be prevented from entering any receiving streams or wetlands.

In addition to water quality monitoring, additional hydraulic data was provided by a network of 16 pressure loggers co-located with conductivity meters (using T connection in hydrants).

Water quality characteristics FTTP is in the process of implementing advanced water treatment technologies that are needed to comply with new regulations. The major components of the advanced treatment projects include granular activated carbon (GAC) adsorption followed by ultraviolet light (UV) treatment. The new GAC adsorption process follows the existing coagulation and filtration processes, and UV provides an additional disinfection barrier to chlorine.The GAC process involves sending water through deep beds of carbon to remove compounds that are present in the raw water. The compounds removed by the carbon may be present naturally in the Ohio River that later react with chlorine to form minute levels of disinfection by-products. The Ultraviolet Light (UV) treatment process will further supplement the current disinfection practices. Using UV followed by chlorine greatly improves the effectiveness of the disinfection process.

Free chlorine concentration of effluent from FTTP was maintained at approximately 1.34 mg/L ranged from 1.11 mg/L to 1.47 mg/L during period of 2012. Fluoride levels in the effluent ranged from 0.83 mg/L to 1.10 mg/L, and average fluoride level was 0.95 NTU. Turbidity levels in the clearwell effluent ranged from 0.02 to 0.2 NTU, and average turbidity was 0.05 NTU.

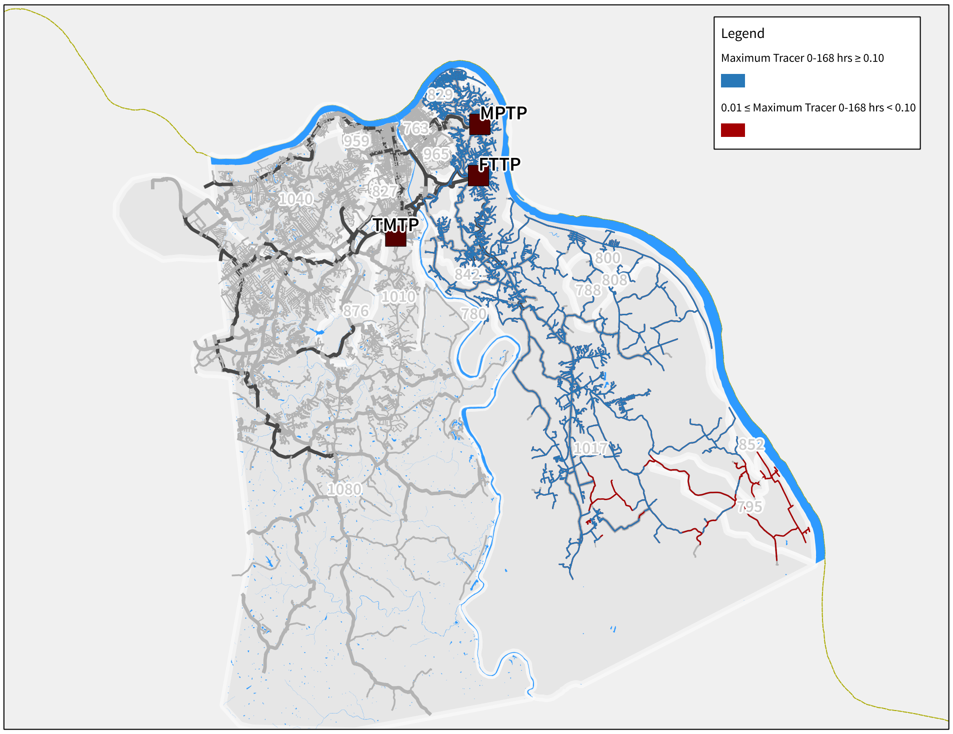

Figure 6: Water network in target study area

Figure 7: Continuous conductivity and temperature analyzer and grab sample tap (typical).

The average conductivity level was detected 425 μs/cm ranging from 306 μs/cm to 546 μs/cm. The average chloride level was 32.5 mg/L ranging from 18.5 mg/L to 51.5 mg/L. The average calcium level was 34.6 mg/L ranging from 28.7 mg/L to 39.6 mg/L.

4 Monitor Location Selection

The objectives of the monitoring location selection process were to identify locations that represented the model-predicted range of hydraulic residence times while provide samples that were: 1) spatially diverse and/or 2) concentrated in more densely populated regions. Using the distribution system network model provided by the utility, water age analysis and trace simulations were performed using EPANET and the existing network model to provide information for the monitoring selection process. Figure 8 provides a map associated with the spatial distribution of water age – separated by quintile values – with the blue symbols representing the monitoring locations.

The monitoring placement was performed manually to locate a total of 46 conductivity sensors. While the overall intent was to place sensors to provide representative sampling locations with respect to spatial distribution and water age, there were additional key locations that were identified as important regardless of the underlying hydraulic characteristics. Specifically, one monitoring station was placed downstream of the injection location, and six monitoring stations were placed on the influent/effluent lines (or nearby locations) of the storage tanks within the study region. For the remaining 39 locations, the intent was to manually identify monitoring station locations to represent the distribution of water age as well as intensely sample a more populated "grid" portion of the network. Thirty of the remaining 39 monitoring stations were placed to have six monitoring stations in each of the water age quintile ranges using visual inspection to spatially distribute the monitoring stations. The remaining nine sensor stations were placed in the more dense, gridded region in the north of the system; three locations were intended to capture the influent water quality into this region and the other six locations selected to provide coverage of the potential characteristics within the region.

4.1 Monitor Devices

The electrical conductivity (EC) signals are measured at every 1 minute interval and logged continuously during the study periods at each location. Each monitoring device is composed of conductivity sensor, signal display, data logging module, battery, and etc, which is shown in figure 10. Conductivity sensor is main component of monitoring devices in this tracer study. 4-Electrode conductivity monitor manufactured from Analytical Technology, Inc. (ATIs Q45C4) is used as a part of monitor device, which can measure a single sensor configuration to be used in conductivity ranges from 0 to 2,000 μS/cm and give output voltage ranging

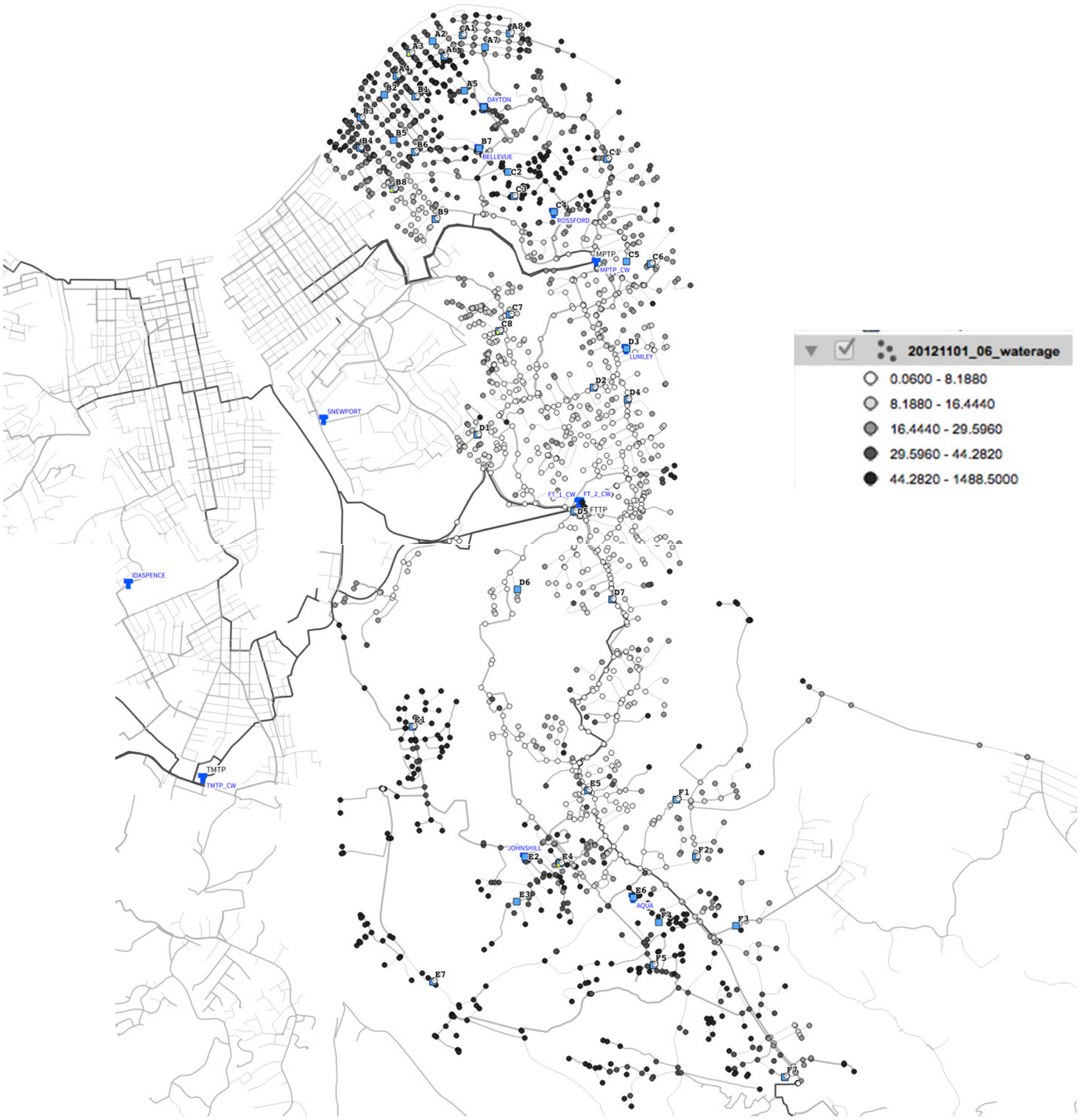

Figure 8: Network model map illustrating the network nodes within the study region that includes the expected water age (grey-scale); monitoring locations are presented in blue.

from 0 to 2.5 V. All monitors are precisely calibrated with 1000 s/cm standards in the EPA T&E facility. All monitor have data logger inside to log EC signals continuously. Two types of data loggers are used as a part of monitor device in accordance of availability. One type is HOBO H8 4-channel logger housed in blue box. The other is Nexsens iSIC logger is housed in grey box. Total 47 monitors were located on the field (type A - 13, type B - 34) including 1 backup device. All monitor were tested for variability between the devices by measuring three different samples in the lab.

4.2 Field Locations

Subareas A to F are shown in Figures 11, 12, 13, 14 and 15, including the sampling locations within each area and the pipe size distribution.

5 Field Test Protocol

The planned activities include applying a calcium chloride ($CaCl_2$) solution as a series of pulses at one location, that the pulses would be applied over a 12 hour period. US27 pump station which is the distribution pump station from the clearwell of Fort Thomas Treatment Plant (FTTP) was selected in consultation with NKWD staff based on safety, security, space, and control aspects. The $CaCl_2$ pulses were measured by 50 continuous specific conductance meters located in the distribution system to provide information about the passage of the specific conductance signatures at high spatial and temporal resolution. In addition to the specific conductance monitors, 16 pressure loggers were placed in the distribution system, and operational data were collected from the SCADA system for the time period of the test to provide additional information and controls on system hydraulics.

In summary, a NSF food-grade $CaCl_2$ solution was added to treatment plant finished water, producing a series of brine pulses of between 15-60 minutes duration each, spaced in time over a 12 hour period. The pulse injection rate was selected to produce a detectable increase in the specific conductance above the background (approximately 400 $\mu S/cm$), and yet maintain a significant safety factor when compared to the maximum allowable $CaCl_2$ increase based on applicable federal and state standards. In between pulses the $CaCl_2$ feed will be discontinued. During the brine addition and for an estimated 2-3 days afterward, the pulse arrival was recorded by data-logging specific conductance meters situated at hydrants and other access points.

5.1 Brine Solution

The U.S. EPA secondary standard on chloride is 250 mg/L. Based on historical data collected from NKWD over several years, the range in chloride concentrations of finished water is

Figure 9: Continuous conductivity and temperature analyzer and grab sample tap (typical).

Figure 10: Monitoring device type B

between 16 and 66 mg/L (given an analysis of finished water data collected between January, 2010 and August, 2011). More recent data from the past year for the distribution system and treatment plants indicate a similar range in chloride concentrations. Assuming a conservative background chloride concentration of 41 mg/L, the applicable standards limit a chloride concentration increase to $(250-41) = 209$ mg/L. There was no applicable Federal or primacy agency standards for calcium, and thus it was regulated based on $CaCO_3$ solubility.

Food grade $CaCl_2$ will be obtained as a pre-mixed 33% (by weight) solution[1]. Assuming a specific gravity of 1.322 @ 60° F, the 33% solution equates to 436.26×10^3 mg $CaCl_2$/L, or 278.71×10^3 mg Cl^-/L.

From a quality control perspective, it is essential to place reliable controls on the volumetric flow rate of the $CaCl_2$ solution injection pump, such that the chloride concentration is within the above regulatory limits. The maximum $CaCl_2$ injection flow rate of the food grade stock solution can be calculated from a mass balance at the injection site,

$$Q^{max}_{CaCl_2} = \frac{209\ mg\ Cl^-/L}{278.71 \times 10^3\ mg\ Cl^-/L} \times Q_{Prod} = (0.75 \times 10^{-3}) \times Q_{Prod}, \quad (1)$$

where $Q^{max}_{CaCl_2}$ is the maximum allowable flow rate of the NSF food grade $CaCl_2$ solution, and Q_{Prod} is the production flow rate (in the force main receiving the injection), with both flow rates expressed in the same units. Knowing the production flow rate Q_{Prod}, obtained from the SCADA system, equation (1) will be used to calculate the maximum injection flow rate for regulatory purposes, both when planning the test and in the field at the time of the

[1]Tetra Chemicals™NFS grade calcium chloride – see attached specification sheet.

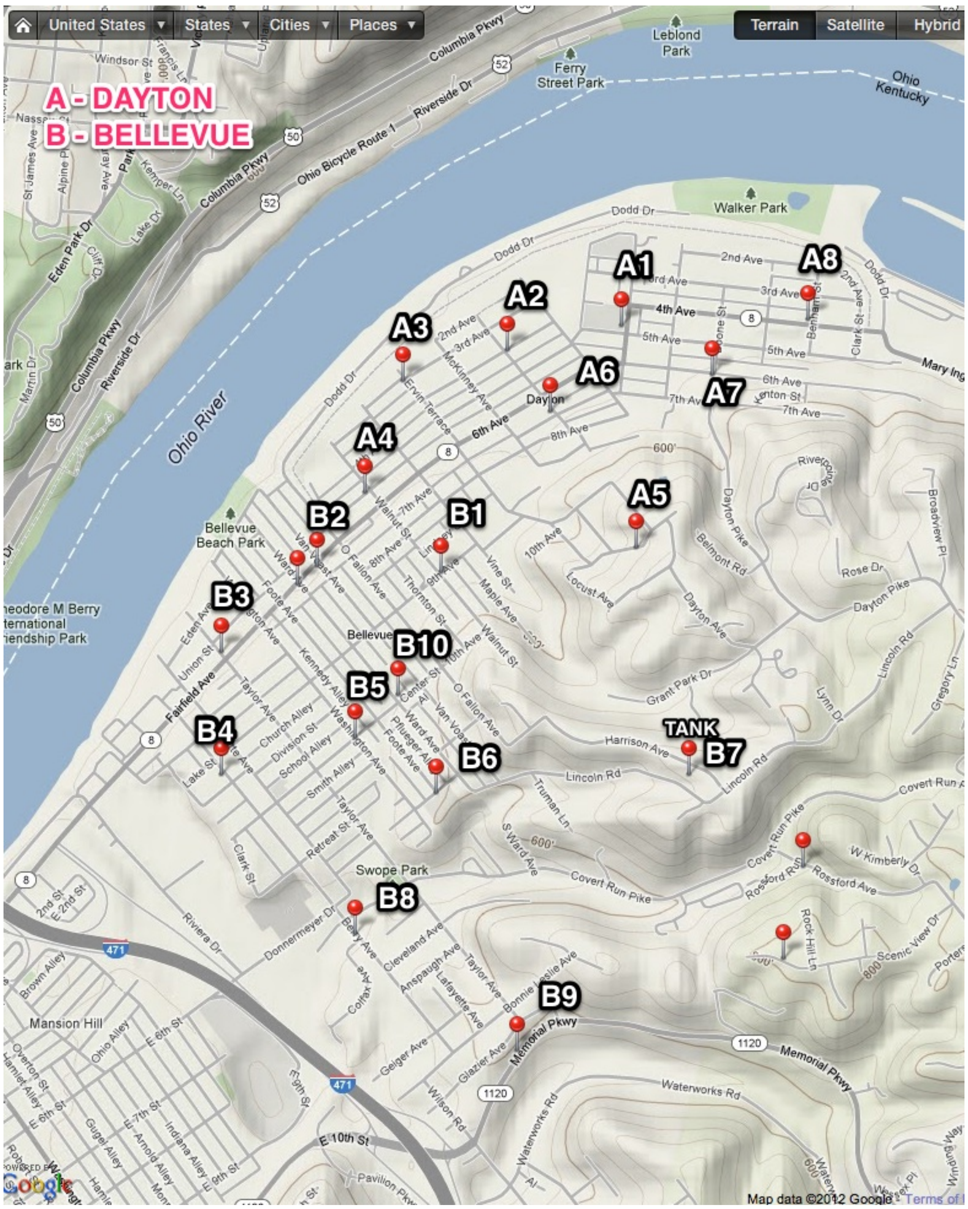

Figure 11: Target study area overview map. Red circle pins are conductivity monitoring locations.

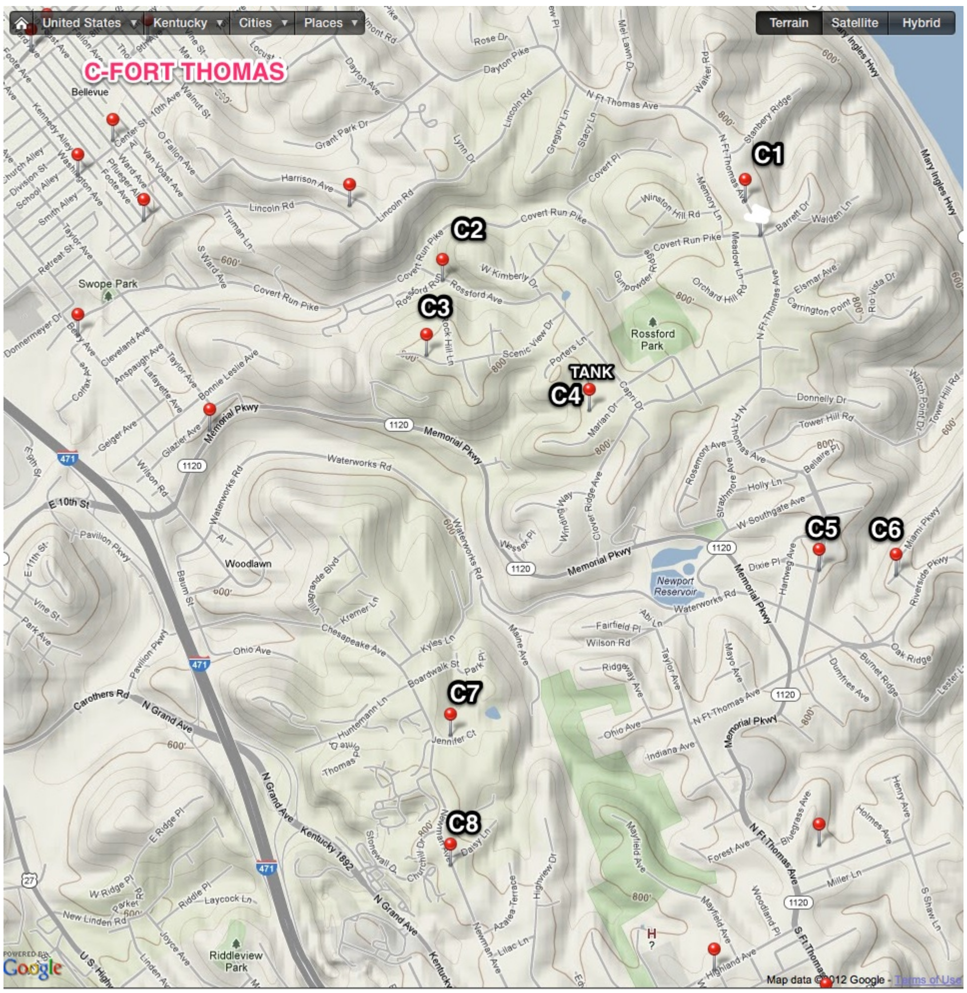

Figure 12: Target study area overview map. Red circle pins are conductivity monitoring locations.

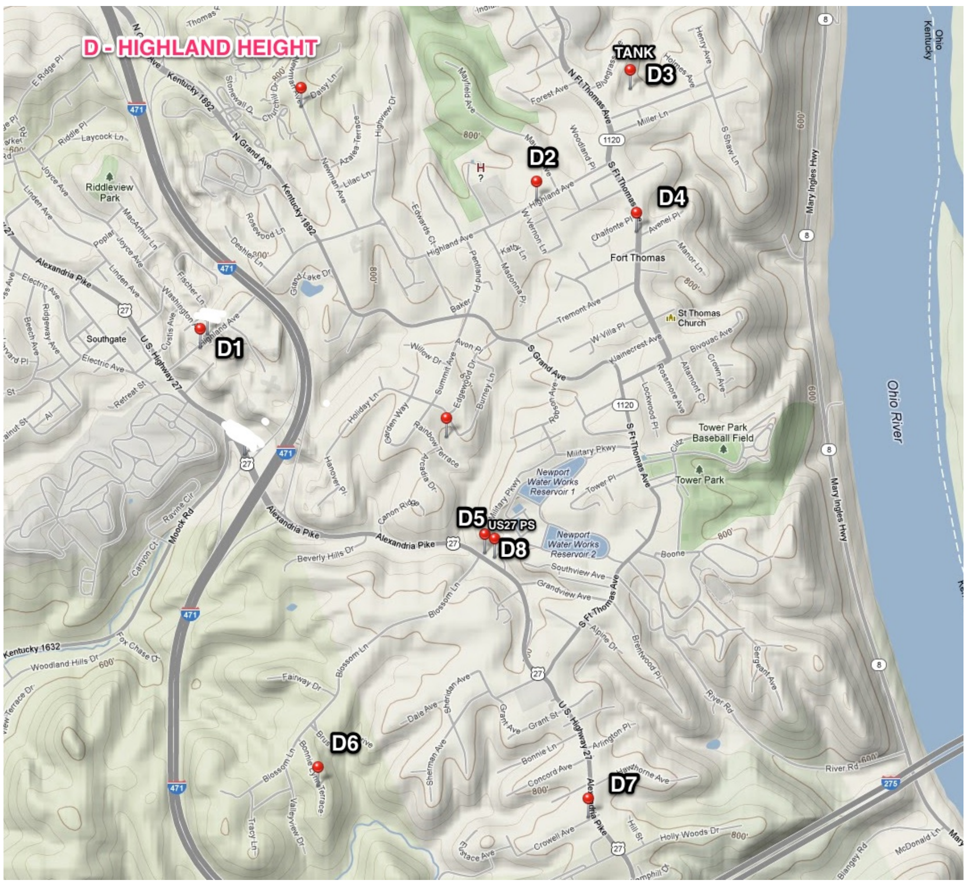

Figure 13: Target study area overview map. Red circle pins are conductivity monitoring locations.

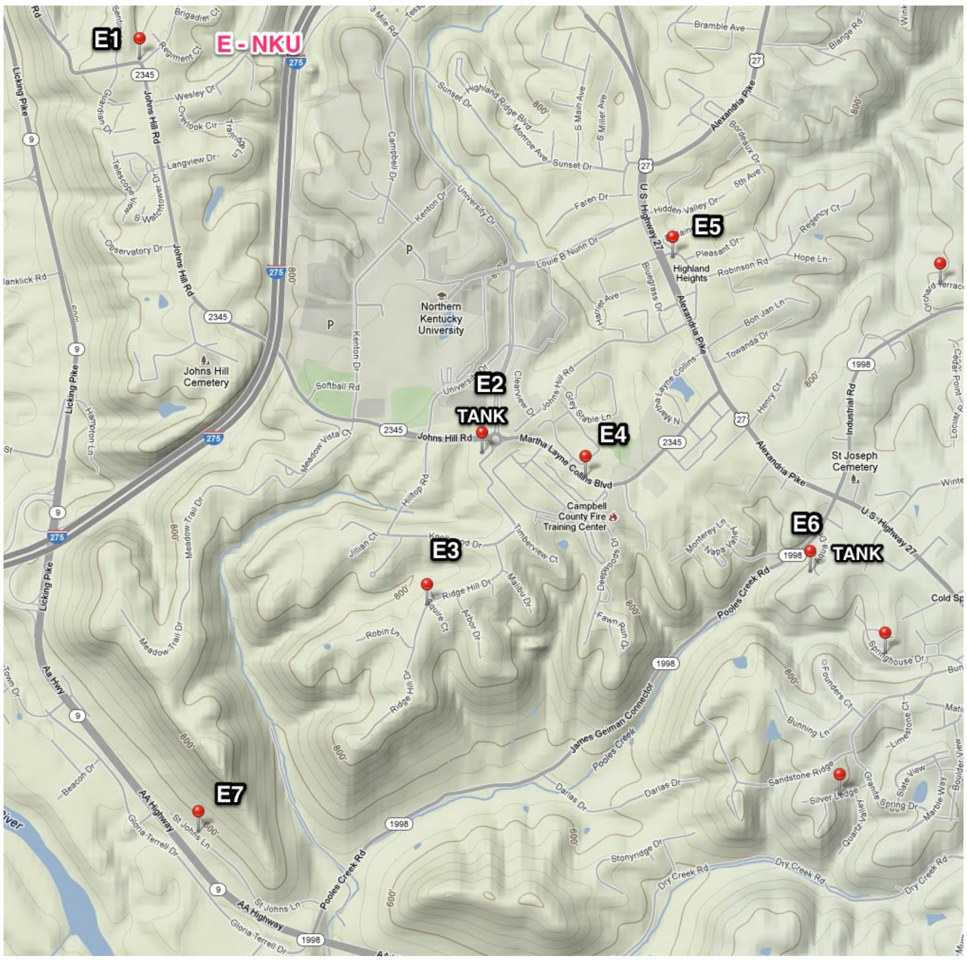

Figure 14: Target study area overview map. Red circle pins are conductivity monitoring locations.

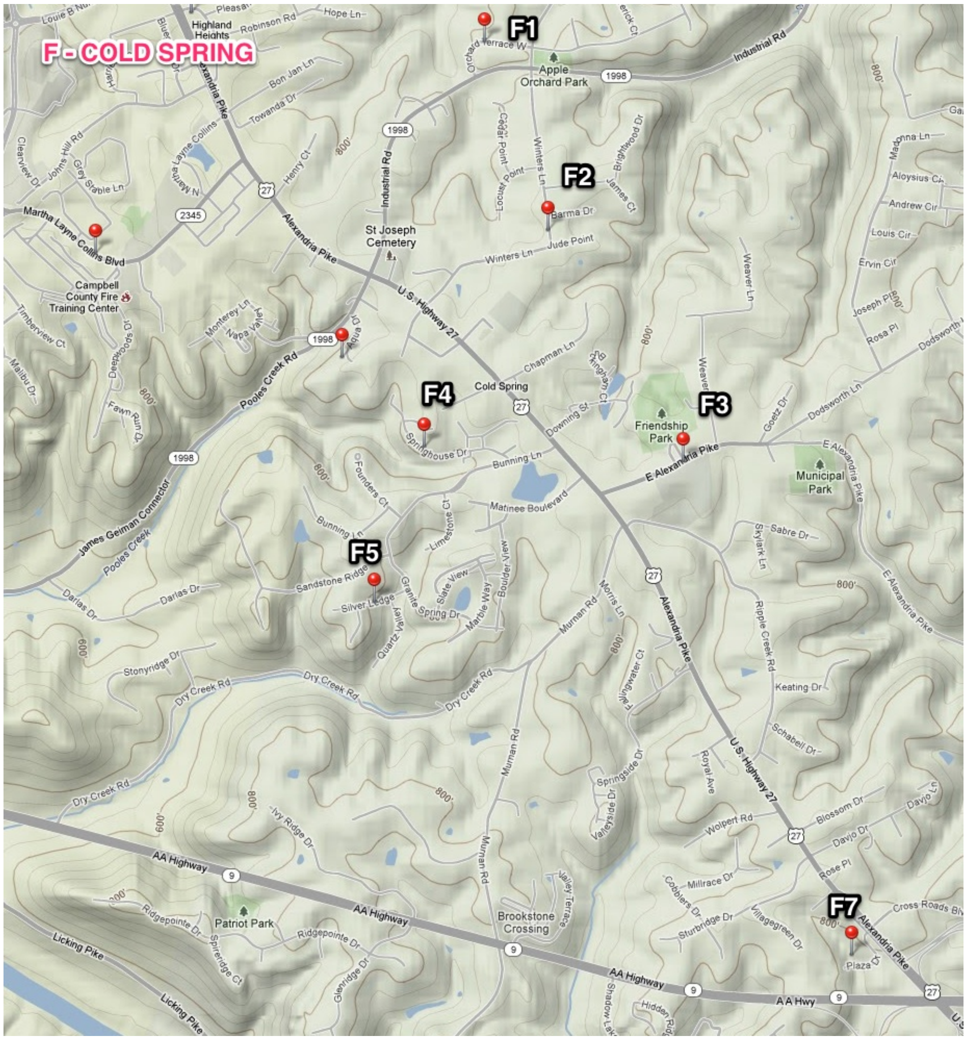

Figure 15: Target study area overview map. Red circle pins are conductivity monitoring locations.

injection. *The adopted test protocol will limit the maximum addition to 80% of this value.* Sufficient volume will be obtained to produce 3-4 salt pulses over a 12 hour period, depending on actual plant production.

For an effective tracer test, the injection of brine must create a measurable increase in specific conductance above background. NKWD reports that the specific conductance in the distribution system varies between 248 and 637 μS/cm. The impact on the specific conductance can be estimated from the relationship between total dissolved solids (TDS, mg/L) and specific conductance (EC, μS/cm),

$$TDS = k_e EC, \tag{2}$$

or,

$$\Delta EC = \frac{\Delta TDS}{k_e}, \tag{3}$$

where the correlation factor $0.5 < k_e < 0.8$. Assuming the maximum $CaCl_2$ injection flow rate from equation (1), the resulting increase in total dissolved solids, ΔTDS, can be calculated,

$$\Delta TDS = 0.8 \times (0.75 \times 10^{-3}) \times (436.26 \times 10^3\ mg/L) = 261.76\ mg/L. \tag{4}$$

Assuming a "worst case" $k_e = 0.8$, we estimate a corresponding increase in specific conductance,

$$\Delta EC = \frac{261.76}{0.8} = 327.2\ \mu S/cm \tag{5}$$

which is $> 80\%$ increase over background; this increase is significant given the accuracy of the specific conductance monitors that will be used. Bench scale testing will determine the correct value of the correlation coefficient k_e, prior to conducting the study, which will allow the estimate of ΔEC to be refined[2]. The final estimate of ΔEC, and thus the target specific conductance after injection, will also give an additional practical control on solution injection, since measurement of EC is essentially a surrogate for direct measurement of the chloride addition. Bench scale testing will also identify the level of salt addition associated with precipitation of calcium carbonate, and will practically eliminate the risk of any precipitate forming during the test.

To determine the appropriate calcium chloride dose, the background concentration of chloride will need to be estimated on the day of the tracer test. To do so, a relationship between historic chloride and specific conductance was developed for water samples collected in NKWD finished water over the past year. A summary of the analysis performed is attached as Appendix A. The analysis shows that based on a measured specific conductance, we can estimate a range for the current chloride concentration (prediction interval) with 99% confidence. A very conservative approach is to assume the high end of this range as the current chloride concentration, meaning we can say, with 99.5% confidence, that the measured chloride concentration will be equal to or lower than the assumed value.

Approximately 1000 gal. of food-grade $CaCl_2$ was used and stored in two 500 gal. reservoir (see Figure 18). This volume was designed to produce at least three, and perhaps four salt pulses over the 12 hour period, depending on actual plant production. The 32% ready-made brine solution was used for this study.

[2]Testing with finished water from the Greater Cincinnati Water Works Miller treatment plant found that $k_e \approx 0.5$ which, if that proves true for NKWD finished water, would allow a doubling of specific conductance above background, with an even larger safety factor on the secondary standard for chloride.

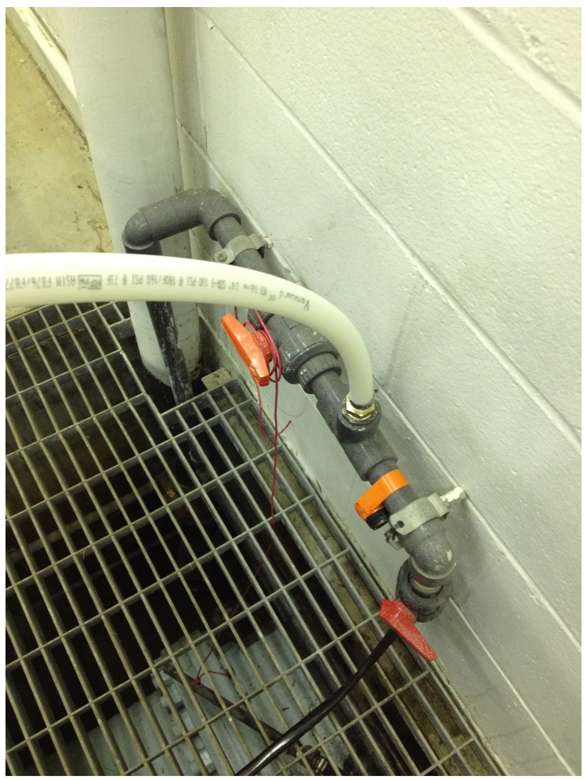

Figure 16: Brine solution injection connection.

Figure 17: Flow meter and injection pipe main outlet.

Figure 18: Brine solution tank.

5.2 Injection

The brine solution was injected into a force main leaving the treatment plant and providing 100% of the study area water demand. Figure 16 shows the point of injection, just before a venturi meter. Brine solution was delivered through a positive displacement pump. Figure 17 shows the magnetic flowmeter which transfers to SCADA database after pumping station.

Field specific conductance measurements The following steps were followed to develop an accurate correlation between specific conductance and chloride between background levels and elevated levels during the tracer study.

1. Sample the stock calcium chloride solution to verify actual concentration as chloride.
2. Develop a correlation between measured specific conductance and volume stock chloride concentration. Several additions of the stock calcium chloride solution will be added to develop a curve that reaches and exceeds the calculated injection concentration.
3. On the day of injection, estimate the current background chloride concentration by monitoring specific conductance and applying the derived correlation between historic specific conductance and measure chloride in NKWD finished water (Appendix A). The assumed background concentration will be chosen at the upper limit of the 99% prediction interval given by the correlation data (as described in Section 5.1).
4. Using the background chloride concentration established in step 3, determine the appropriate pump rate in combination with current plant flow (as described in Section 5.1) to target the injection concentration.

Injection Pulses At the start of each separate injection, the injection flow will be increased in discrete stages up to its target flow rate. A specific conductance meter was located downstream from the injection site, on the same force main, but a sufficient distance down-gradient to allow for complete mixing of the brine solution. Feedback on the specific conductance level at this downstream monitor was used to confirm the impact of each staged increase in injection flow rate, prior to proceeding to the next injection level. Table 2 summarized 4 injection pulses along with time and instantaneous conductance value in display.

A saturated $CaCl_2$ solution was added to the treatment plant finished water beginning at 8:43 AM on 19 November 2012. The first injection was started with 10 Hz of injection pump and halted at 8:57 AM since it didnt appear at the outlet hydrant. It was re-started again with 10 Hz injection speed at 9:02 because injection started to appear at the outlet hydrant of injection site. The pulse rate of displacement pump was increased to 13 Hz at 9:19AM and the increased conductivity measured about 750 μs/cm at outlet hydrant. The

Figure 19: Brine injection pump with volumetric flow measurement device.

Table 2: Estimated conductivity and fluoride concentration leaving the treatment plant during the 12-hour injection period.

Injection Pulse	Phase	Start Time	End Time	Pump Speed (Hz)	$CaCl_2$ Flow Rate (L/min)	Electrical Conductivity (μs/cm)	Chloride Concentration (mg/L)
1st Injection		8:43	8:57	10			
	Restart	9:02	10:12	13	7.61	750	143
2nd Injection		13:14	14:35	13	7.3	750	
	Changed			14	8.25	815	174
3rd Injection		17:17	18:35	15	8.76	870	180
					8.97		
4th Injection		19:26	20:45	16	9.55		154

salt flow rate was confirmed as 7.61 L/min at 10:08 when pump was pumping into main with pressure which was a little low but not so low as to explain the low conductivity. The first injection stopped at 10:12 AM. The injection period of 1st pulse is about one and half hours.

2nd injection was started at 1:14 PM at 13 Hz speed which was the same as first injection. The conductivity measured at inside pump house (station id D5) in 24 force main at about 750 which was still plateaus. $CaCl_2$ injection flow rate was measured 7.3 LPM. The flow measured about 3600 gpm. Injection pump speed was increased to 14 Hz and flow rate was measured at 8.25 LPM. Conductivity was increased to 815 μs/cm. Injection 2 stopped at 2:35PM.

3rd Injection was started at 5:17PM with 15 Hz of injection speed and the measured flow rate was 8.76 LPM at injection pump. Injection 3 stopped at 6:35 PM. The $CaCl_2$ flow rate measured 8.97 LPM just prior to stopping injection, and read between 830 μs/cm and 870 μs/cm conductivity.

4th Injection was started at 7:26PM with 16 Hz of pump speed. The $CaCl_2$ flow rate measured 9.55 LPM. Injection 4 stopped at 8:45 PM

Figure 20 presents the designed conductivity concentrations during the 12-hour tracer injection period (time zero in figure 20 is the start of injection). The design called for three pulses, but sufficient brine solution was left after the third pulse to create a fourth of approximately 2.5 hours duration.

The project team was concerned about attenuation and loss of integrity of the conductivity pulses, due to flow splitting and recombination in the looped areas of the distribution system. These processes are inevitable, but logically there is an optimum configuration of pulses that would provide maximum flow information. As one extreme example, a single pulse of infinite duration would provide flow and velocity information only during the single step change from background conductivity. Although the information content in the output conductivity signal is related to the excitation in the input signal, too many or too frequent

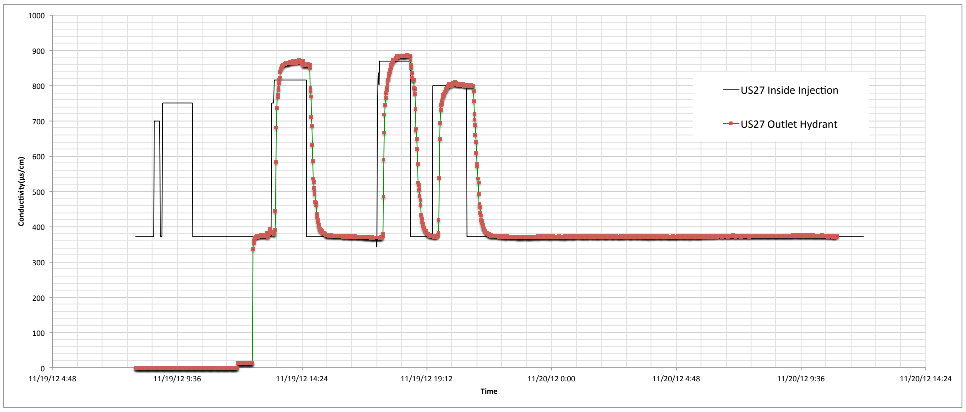

Figure 20: Estimated conductivity and fluoride concentration leaving the treatment plant during the 12-hour injection period.

pulses might lose their distinctive signature, and require complex (and new) data analysis approaches. The field protocol was designed to use a range of pulse durations and spacing, so that the data might provide useful information for future tracer experiments.

Chloride sample tests Specific conductance measurements was used as a surrogate to monitor chloride concentrations in the distribution system following the brine injections. Given the accuracy of the specific conductance monitors, the monitoring of chloride concentrations in the potable water and what is discharged from each hydrant was both accurate and efficient. Monitored specific conductance measurements will then be used to report chloride concentrations in the distribution system and released from the hydrants. A chloride sample will be collected and analyzed during each tracer pulse at the first sampling location downstream from the injection site. The relationship developed between chloride concentration and specific conductance will be used to determine chloride levels at monitoring stations, based on measured specific conductance.

In addition to field water quality measurement, four bottle tests at each injections were conducted using finished water leaving the plant during the 12 hour injection period. Chloride analysis of sample collected at approximately mid-way through each injection period. Four samples were collected to measure chloride concentration changes in MCL standard (250 mg/L) due to injections throughout the study. Chloride level measured during the 1st injection to 4th injection were 143 mg/L, 174 mg/L, 180 mg/L, and 154 mg/L. None of injection violates MCL standard.

Field Water Quality Measurements The study was designed to measure changes in water quality of the volume of water leaving the treatment plant during the 12 hour injection period. The conductivity concentration would provide near real-time evidence of water movement, and field water quality sampling would adapt by moving downstream, following the traced water volume. Prior simulation of distribution system residence times and flow paths provided an estimate of the test duration and how the sampling network would be extended. Conductivity data was collected from the continuous loggers periodically, and plotted to visually show tracer movement.

6 Results

6.1 Pressure Monitoring Results

Water pressure data have been collected to calibrate hydraulic model in the pilot study area as a part of tracer study. For this purpose, 9 Dickson pressure loggers and 16 Radcom LoLog 450 pressure loggers were installed to collect water pressure from 11/19/12 to 11/26/12 all around the system. All loggers were set up 3 minutes of sampling interval. One of Dickson pressure loggers was unable to collect data for the defined period and 3 of them collected the data from 11/24/12 to 11/26/12 due to unknown technical problems. But the other loggers collected the pressure data successfully. Locations of installed pressure loggers are depicted in Figure 1.

Figures 21, 22, 23, 24, 25, and 26 summarize the conductivity monitoring data at each site from A to F. No adjustments to or filtering of the data have been made.

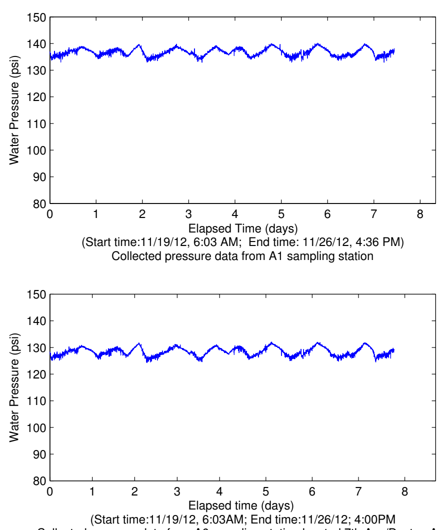

Figure 21: Pressure monitoring results in region A. Pressure loggers were installed at A1, A4, and A6 stations

Installed pressure logger on B1 sampling station was unable to store pressure data.

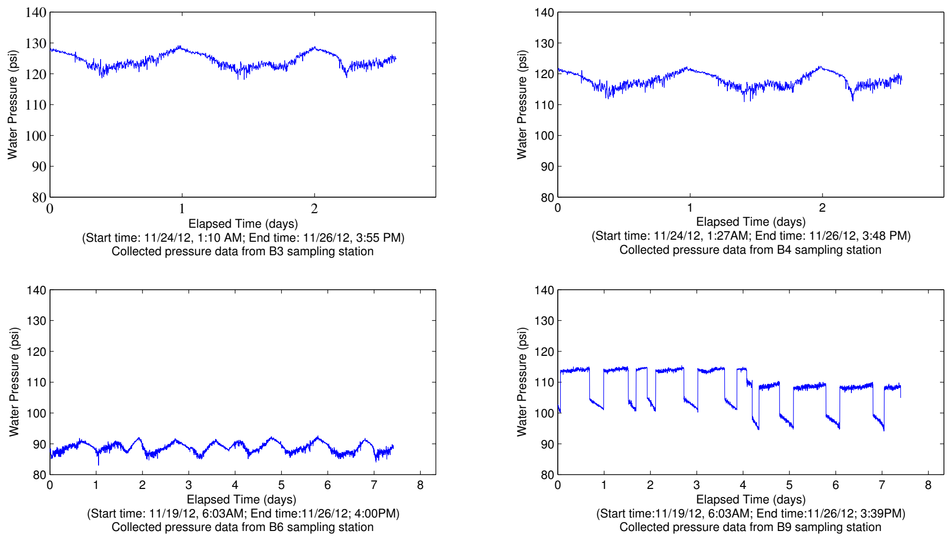

Figure 22: Pressure monitoring results in region B. Pressure loggers were installed at B3, B4, B6, and B9 stations

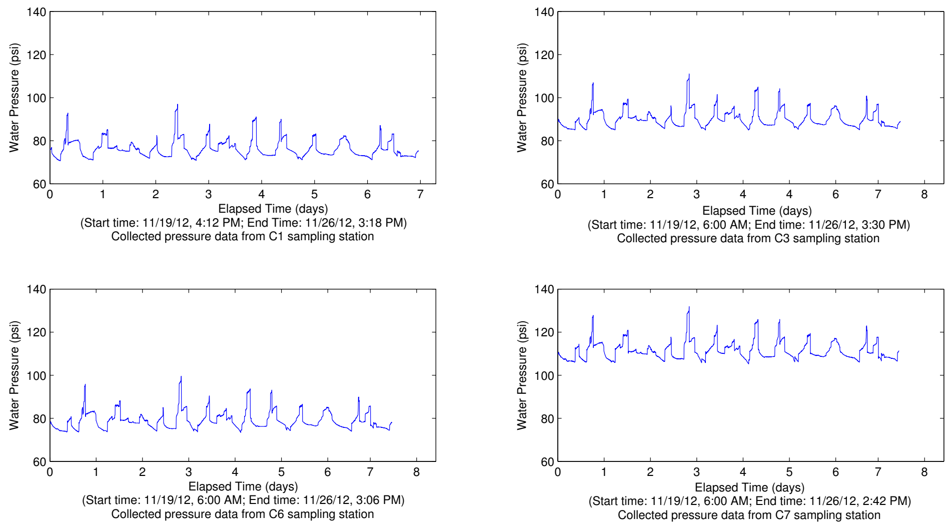

Figure 23: Pressure monitoring results in region C. Pressure loggers were installed at C1, C3, C6, and C7 stations

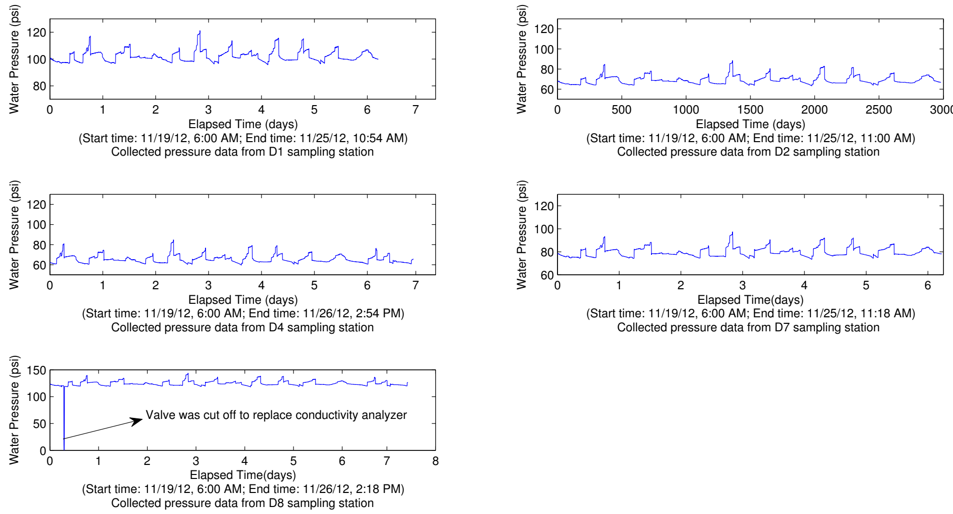

Figure 24: Pressure monitoring results in region D. Pressure loggers were installed at D1, D2, D4, D7, and D8 stations

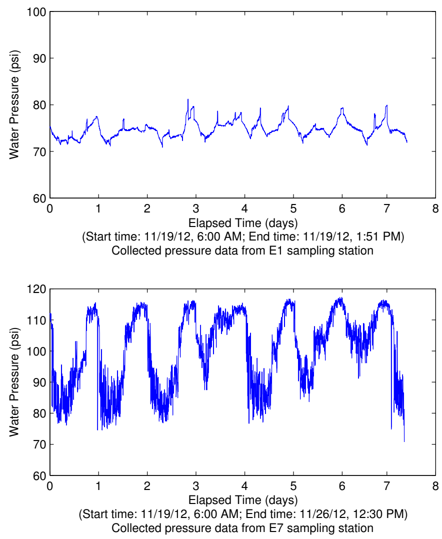

Figure 25: Pressure monitoring results in region E. Pressure loggers were installed at E1, E5, and E7 stations

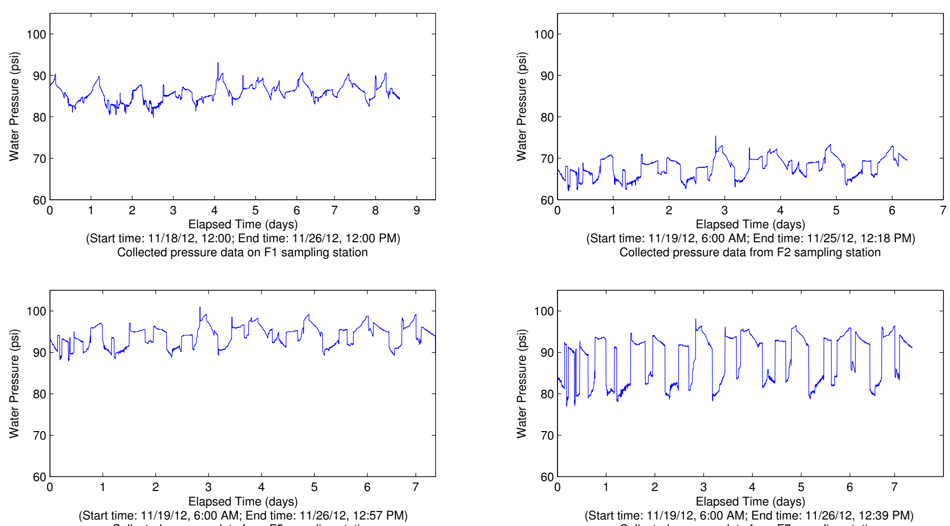

Figure 26: Pressure monitoring results in region F. Pressure loggers were installed at F1, F2, F5, and F7 stations

6.2 Tracer Signal Data - Observed data description

The observed conductivity signals from the 38 monitoring sites are grouped and plotted as regions A through F. The selection of these regions was primarily based upon physical proximity for the implementation of the field study rather than hydraulic connectivity. Regrouping of the locations may be performed once the hydraulic model has been updated and simulated data are available. The following paragraphs present the observed data for each of the six regions.

Figure 27 shows the locations of eight monitoring stations in Region A (location B1 will be discussed in the next section) and the observed conductivity signals over a three day period of the tracer study. This area was one of the heavily monitored regions to provide more measurements within a more densely populated region of the system. No data was presented for Location A1 because the conductivity unit malfunctioned within the field study. With the exception of A5, which was just outside of the "gridded" portion of Region A, the conductivity signals for Locations A2 – A8 showed very similar conductivity signals. These results were somewhat surprising given the significant amount of cross-connected pipes within this region. The observed signal for Location A5 appeared to be similar to the other locations, but shifted later in time and a bit more smoothed. The data for Locations A6 and A7 were truncated after 1.25 and 2 days, respectively, due to data recording problems with the equipment during the study.

Figure 28 shows the locations and observed conductivity signals for the six monitoring stations in Region B, which were also located in a densely populated region of the distribution system. While Locations B1 through B5 presented some similarity in the observed data, these signals are not nearly as consistent as the signals for the monitors within Region A, which was also a gridded system. Location B7 was located at the Bellevue tank; the square pulses originating near the 1.5 day and 1.8 day times are representative of the tank draining. The signal from Location B9 was very similar with those in region A, suggesting some degree of hydraulic connectivity between regions A and B. For Locations B4, B6, B8 and B10, no data was presented because the units malfunctioned during the field study.

Figure 29 presents the seven locations and conductivity signals associated with Region C, which was located on the southern side of regions A and B. Location C1 appeared to have a significantly different conductivity signal than the other locations within Region C with the differences not immediately clear. Location C8, which is in the southern portion of this region and closest to Region D, appeared to have conductivity signals more closely related to those in Region D. Location C4 represents the conductivity signal associated with the Rossford Tank. Locations C2 and C3 appeared to have signals more closely related to the conductivity signal associated with the tank (C4), which was consistent with the hydraulic analysis performed to identify the monitoring locations. Locations C6 and C7 appeared to have similar conductivity signals suggesting similar upstream connections. No data for Location C5 was presented because the conductivity monitor malfunctioned during the field

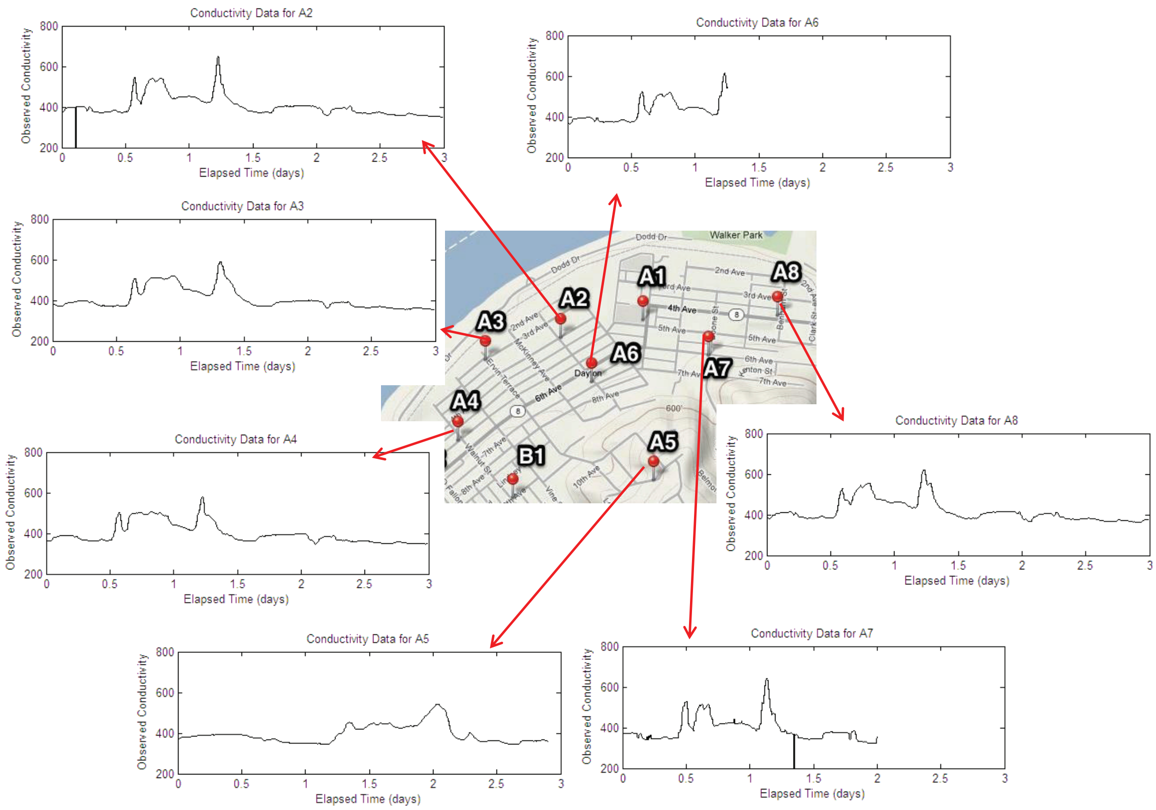

Figure 27: Plots of monitoring locations and conductivity signals for Region A; Conductivity signals for A1, A6 and A7 were not displayed (A1) or truncated (A6 and A7) due to operational malfunctions during the field study.

study.

Figure 30 presents the locations and conductivity signals of the five monitoring stations within Region D, which is south of Region A and includes the injection location. Location D8, which was located just outside the tracer injection site, was missing the first few hours of data due to moving the equipment from one location to another to replace a malfunctioning unit at the injection location (D5). Locations D6 and D7 appeared to be consistent with the data from LocationD8 with the former showing more spread in the observed conductivity signal. The signal from Location D1 was less intense and appeared to demonstrate impacts from a tank based on the apparent square pulses observed just past the 1.5 and 2 day marks. Location D3, the Lumley tank, showed the conductivity signal from the storage tank. The conductivity signals from Locations D2, D4 and D5 were not presented as the conductivity units malfunctioned during the field study.

Figure 31 shows the five locations and observed conductivity signals from Region E of which two locations were tanks (E2 and E6). Locations E1, E2 and E6 appeared to have some similarity in the conductivity signal suggesting that these locations received water from a common upstream location. However, Location E4, which is spatially close to the Johns Hill tank (E2) had a significantly different observed conductivity signal. Locations E2

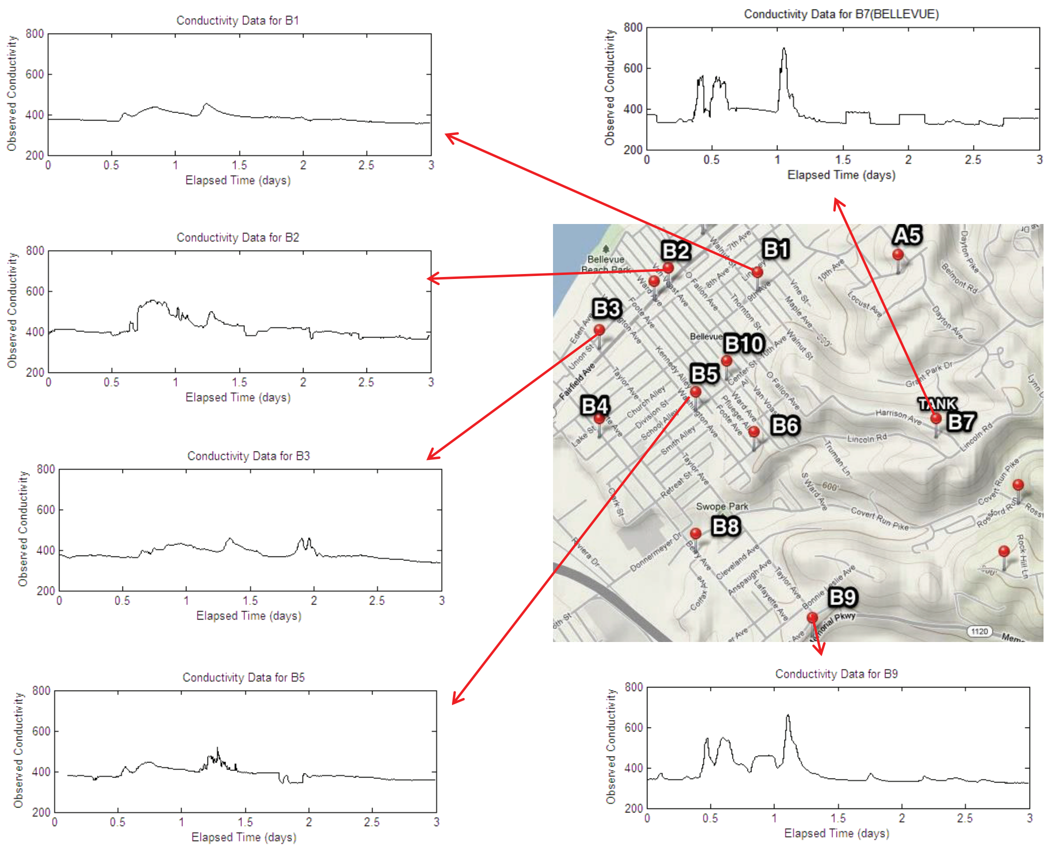

Figure 28: Plots of monitoring locations and conductivity signals for Region B; Conductivity signals for B4, B6, B8 and B10 were not displayed due to operational malfunctions during the field study.

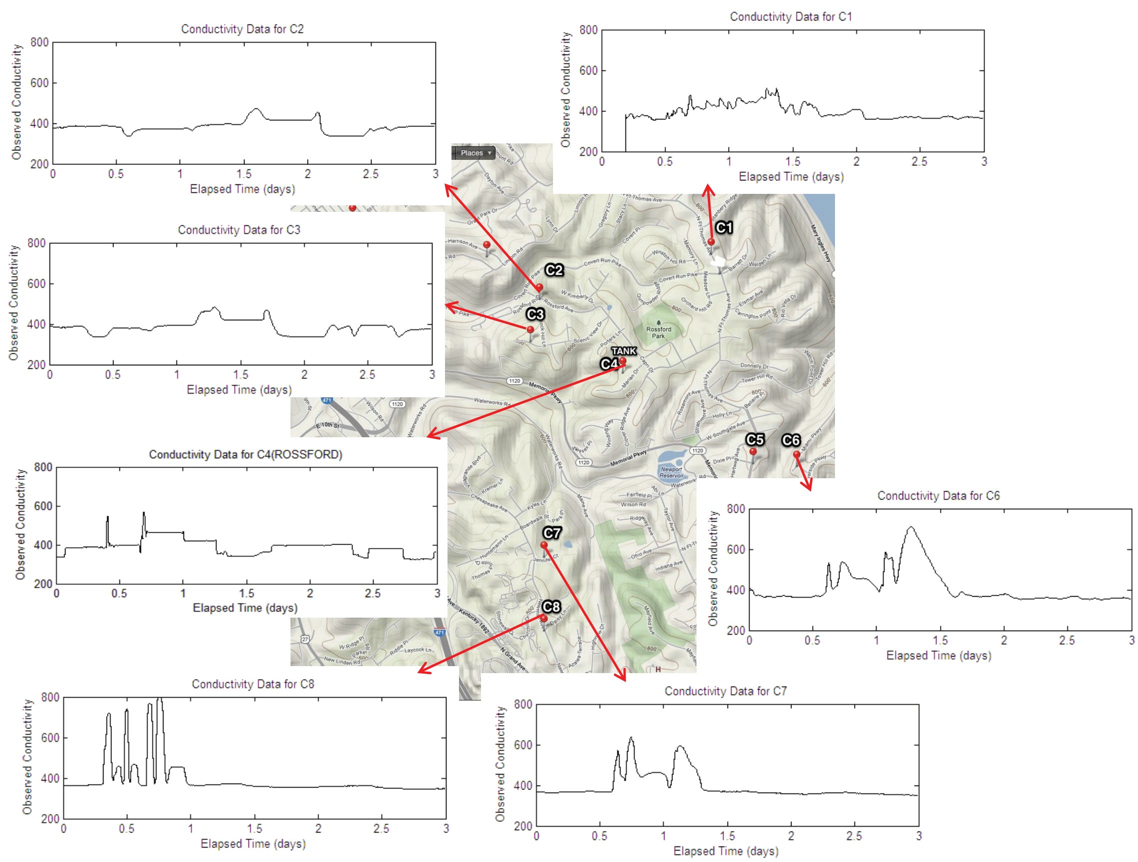

Figure 29: Plots of monitoring locations and conductivity signals for Region C; Conductivity signals for C5 were not displayed due to operational malfunctions during the field study.

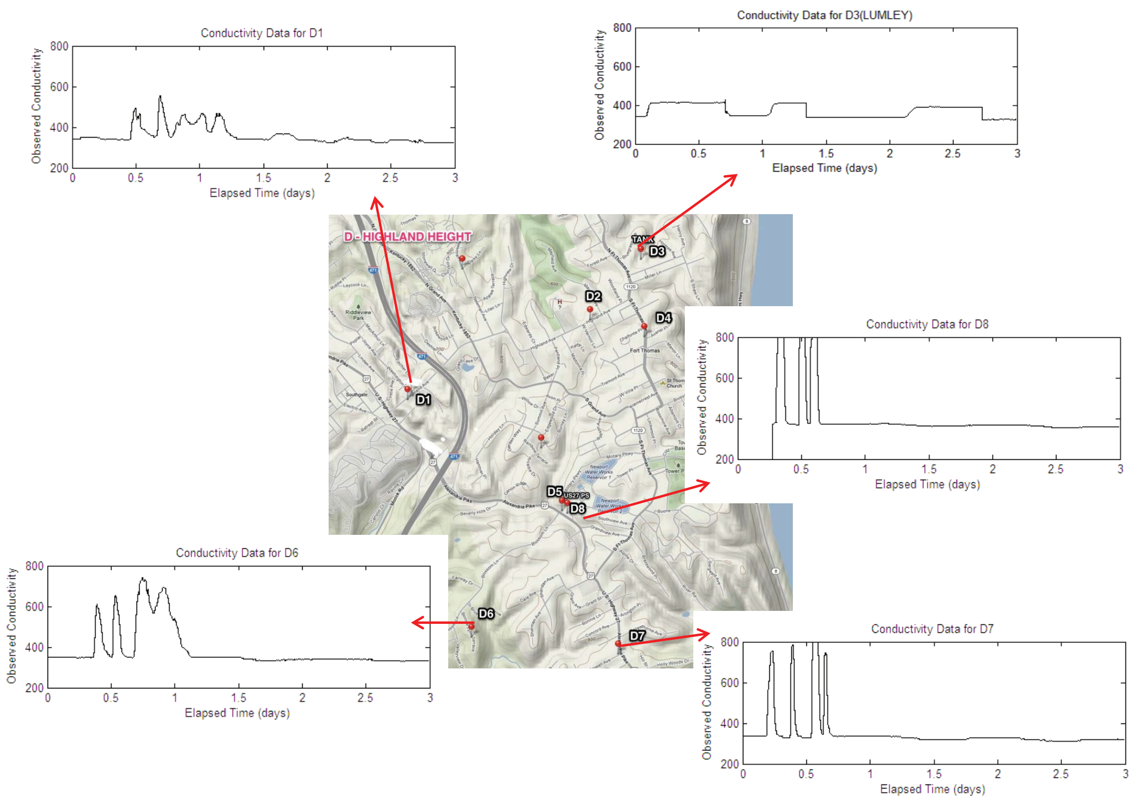

Figure 30: Plots of monitoring locations and conductivity signals for Region D; Conductivity signals for D2, D4 and D5 were not displayed due to operational malfunctions during the field study.

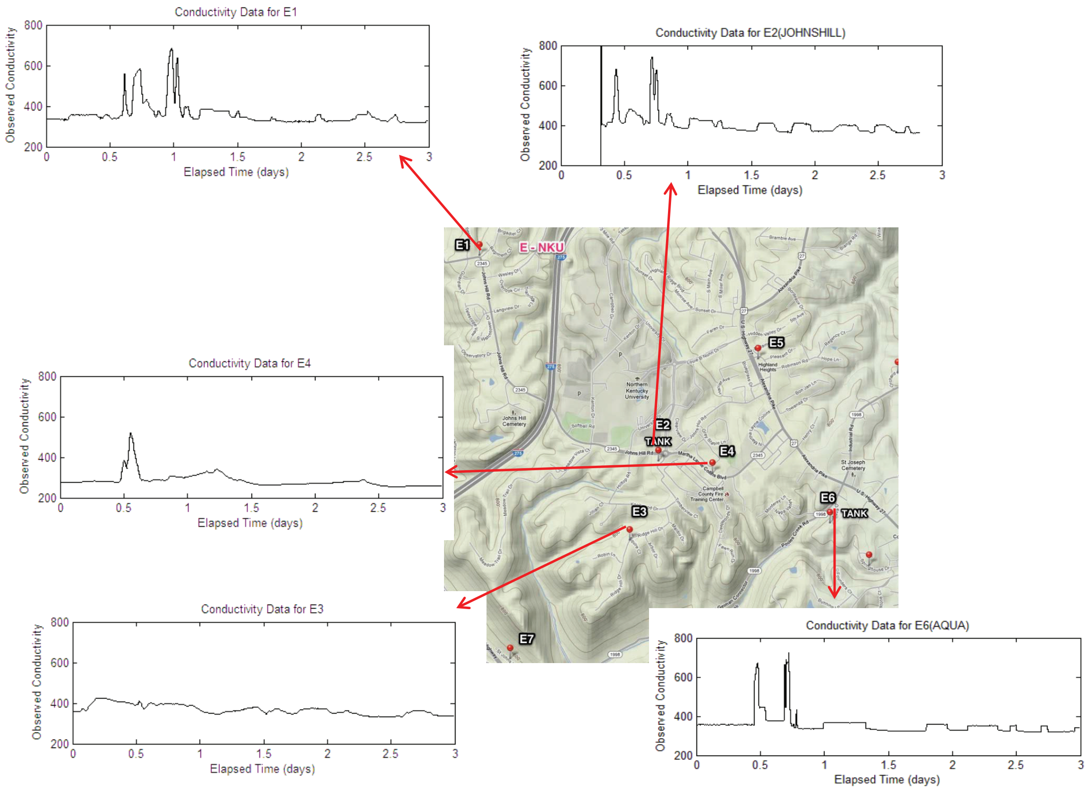

Figure 31: Plots of monitoring locations and conductivity signals for Region E; Conductivity signals for E2 and E5 were not displayed (E5) or truncated (E2) due to operational malfunctions during the field study.

(Johsn Hill) and E6 (Aqua) were both tanks that were monitored by conductivity meters, which demonstrate the square waves associated with tank effluent conductivity. Location E3 appeared to be influenced by the tracer injection, however the resultant conductivity signals have been significantly degraded by the time the signal arrived at this location. The data from Location E2 was truncated after about 2.8 days, and Location E5 was omitted due to the malfunction of the conductivity monitor at this location.

Figure 32 shows the six locations and observed conductivity signals for Region F. Locations F1 and F2 appeared to observe the four peaks of the tracer injection. Locations F4 and F5 demonstrated that some peaks were observed, but there appears to be additional attenuation and/or mixing of the signals. Location F3 shows a strong peak at about 0.5 days, but only one (although a second peak might be comingled within the one), and a smaller peak after 2 days. Location F7 appeared to have a similar temporal range associated with the tracer signals, but distinct peaks associated with the four individual injections were not clearly observed. There was no data presented for Location F6 due a malfunction in the conductivity meter after deployment. The conductivity signals for Locations F2 and F4 were only presented up to 2. 5 and 1.5 days, respectively, due to data recording problems with the equipment during the study.

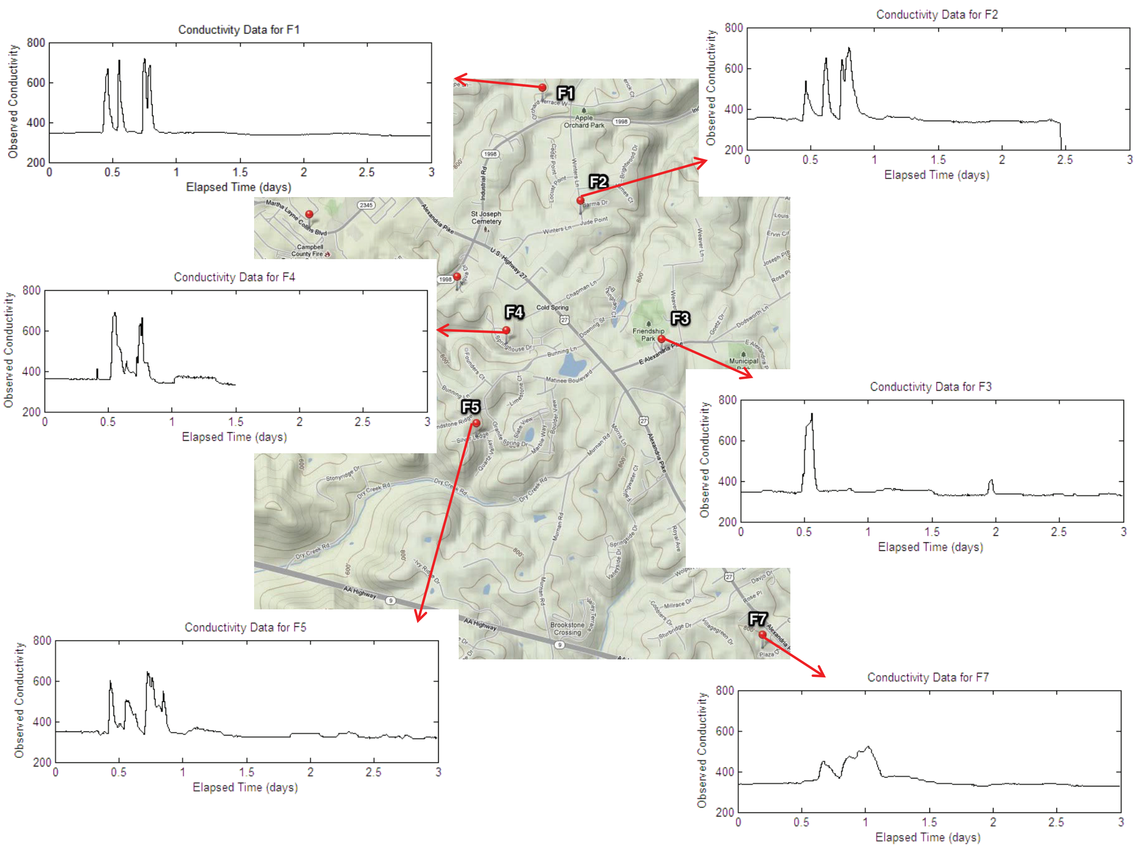

Figure 32: Plots of monitoring locations and conductivity signals for Region F; Conductivity signals for F2 and F4 were truncated due to operational malfunctions during the field study.

7 Data Analysis

Note: The data analysis and discussion is ongoing in the context of developing the real-time model. The brief discussion here is meant to convey the data analysis that is being performed and that will be reported in a subsequent report on real-time model accuracy.

7.1 Hydraulic model calibration

The first step in water quality model development is to construct a suitably detailed, dynamic, hydraulic model. The conductivity data collected from the field will be used to assess existing hydraulic model accuracy, by comparing field conductivity measurement to model predictions. A second version of the model will be produced using base demand data from the November 2012 billing cycle, and adjusting the plant output over time to match flow records from the study period. A third version of the hydraulic model will be developed by varying the spatial demand allocation, or other factors as determined by model deficiencies. Because the tracer information is directly related to flow rates and velocities, a deficient hydraulic model will be easily identified. The methodology to be used for model calibration has not been determined, however, and robust, ready, algorithms for solving this problem do not exist.

Once hydraulic model errors have been quantified and reduced, free chlorine decay kinetic coefficients will be obtained from the bottle test data, and disinfection by-product formation models will be developed and tested using data generated from the pilot study.

7.2 Real-time hydraulic and water quality simulation

After tracer data have been collected and visualized, they will be used to test the accuracy of real-time hydraulic and water quality models. These real-time models will reflect the actual distribution system operational decisions during the tracer study, as well as the actual demands and plant production rates. A summary of model predictions versus tracer measurements will be a valuable set of information for determining the level of confidence to attribute to real-time water quality modeling, as well as a useful dataset for additional model calibration activities.

8 Acknowledgements

The team wishes to thank a variety of individuals for their valuable efforts, without which the study could not have taken place. John Hall, Jeff Szabo, and Terra Haxton assisted with setting up and locating field water quality sampling stations and making sure the monitoring devices were working properly, and with Shaw Environmental provided support for calibration of monitoring devices. Joe Goodin from the University of Kentucky also assisted with setting up the water quality sampling stations. Morris Maslia from the Centers for Disease Control was instrumental in helping to secure necessary field equipment. This work was supported through a contract from the National Institute of Hometown Security: HSHQDC-07-3-00005 "Studying Distribution System Hydraulics and Flow Dynamics to Improve Water Utility Operational Decision Making".

9 Disclaimer

The U.S. Environmental Protection Agency's (EPA) Office of Research and Development participated and helped to support the research described here. The views expressed in this report are those of the authors and do not necessarily reflect the views or policies of EPA. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

A Appendix A: Prediction accuracy of chloride levels based on measured specific conductance

The purpose of this analysis was to estimate the accuracy of chloride level estimates based on specific conductance. Paired chloride and specific conductance measurements collected from NKWD finished water (Fort Thomas Treatment Plant) between 9/7/11 and 8/22/12 were used in this analysis.

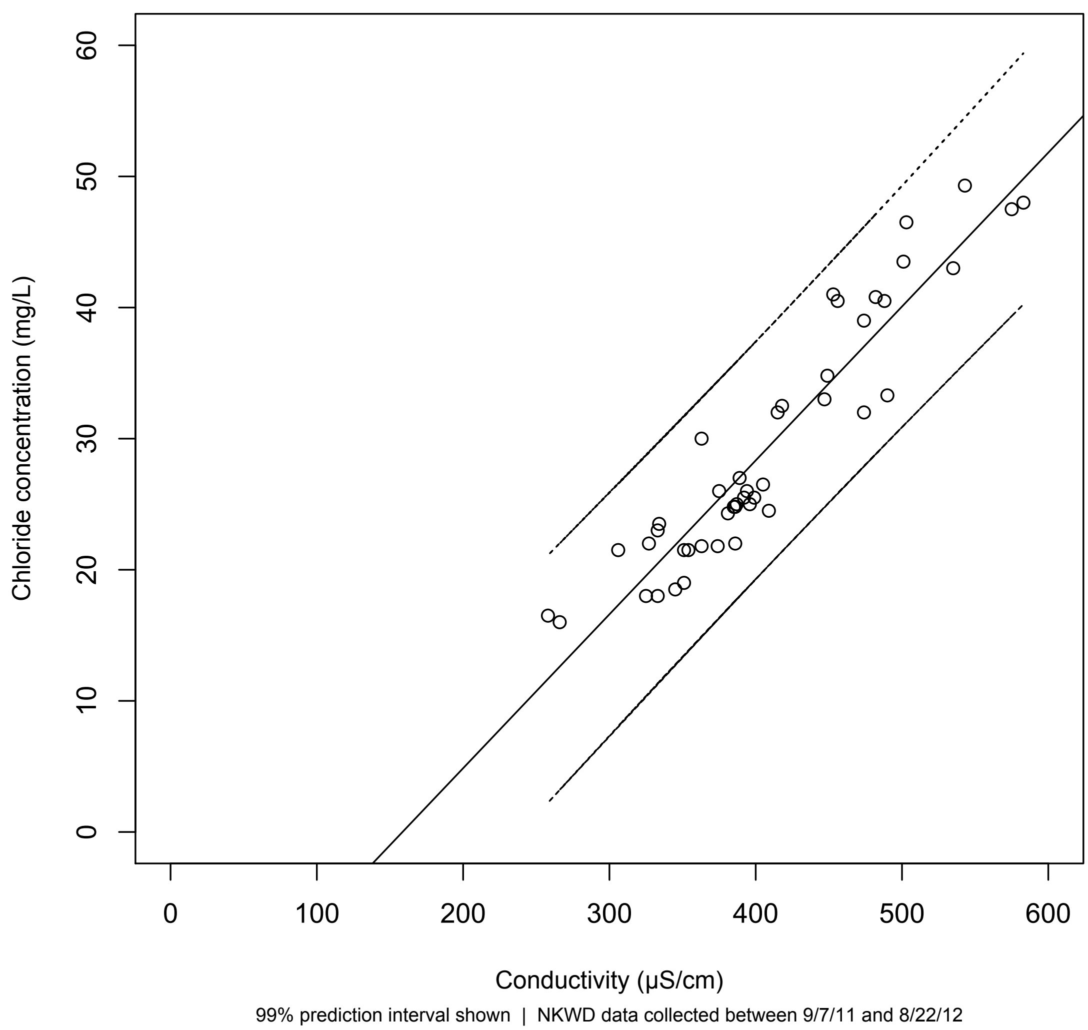

Figure 33: Relationship between specific conductance and chloride measurements

A simple linear regression model was applied to the data set (Figure 33). The prediction interval at a 99% confidence level was calculated. This provides the ability to determine a range for chloride concentration based on a given specific conductance, and based on this data set. The following equation represents the lower bound ($[Cl^-]_{lb}$)on the prediction interval:

$$[Cl^-]_{lb} = 0.117EC - 27.5, \tag{6}$$

The upper bound ($[Cl^-]_{ub}$) is found by:

$$[Cl^-]_{ub} = 0.118EC - 9.68, \tag{7}$$

Using these two equations for a measured specific conductance value provides the 99% prediction interval on chloride concentration in that sample. For example, given a measured specific conductance of approximately 400 $\mu S/cm$, we can be state that the measured chloride concentration will fall between 19 and 37 mg/L, with 99% confidence.

B Appendix B: NSF Grade Liquid Calcium Chloride Product Data Sheet

NSF GRADE LIQUID CALCIUM CHLORIDE

Product Data Sheet

TETRA

TETRA CHEMICALS

General Description

NSF Grade liquid calcium chloride ($CaCl_2$) is an odorless, slightly alkaline, colorless fluid with a typical concentration of 28 to 38 percent.

Applications

TETRA NSF Grade liquid calcium chloride is used for water treatment and complies with ANSI/NSF 60.

Availability

NSF Grade liquid calcium chloride is available from select plant and terminal locations throughout North America. For the location nearest you, refer to the plant and terminal map available on our website (www.tetrachemicals.com) or contact your TETRA sales or customer service representative.

Safety and Handling

Calcium chloride liquid is a strong salt solution. Protective clothing, rubber gloves and eye protection are recommended. Rubber safety boots should also be worn in work areas, since calcium chloride can damage leather. This product should be handled in areas with proper ventilation. Before using this product, refer to the MSDS (available on the Company's website) for complete safety and handling guidelines. For proper disposal guidelines for calcium chloride wastes, consult the appropriate local regulatory authorities.

PHYSICAL PROPERTIES	
Appearance	colorless liquid
Odor	None
Assay	28 to 38% by weight $CaCl_2$
Crystallization Temperature	-38°F (-39°C) to 42.1°F (5.6°C)
Specific Gravity @ 68°F (20°C)	1.264 to 1.3785
Bulk Density	10.53 to 11.49 lb/gal

CHEMICAL PROPERTIES	
Chemical	$CaCl_2$
pH	Slightly alkaline
Impurities (on 100% $CaCl_2$ basis)	
Alkali Chlorides	< 0.1% by weight
Magnesium (as $MgCl_2$)	< 0.1% by weight
Other Impurities (not H_2O)	< 1.0% by weight

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