STUDYING DISTRIBUTION SYSTEM HYDRAULICS AND FLOW DYNAMICS TO IMPROVE WATER UTILITY OPERATIONAL DECISION MAKING

PHYSICAL MODEL DESIGN AND CONSTRUCTION REPORT

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INTRODUCTION

The research objective for this portion of the project is to develop both a physical and computer based water distribution network model. This task is in support of the larger project research goal of developing an operational toolkit for handling the security risks associated with an intentional or unintentional contaminant intrusion. This component of the research project was the development of a laboratory scaled physical model to simulate the flow conditions of a true municipal system. This physical model would act as an aid to the real time network modeling. Since using real time modeling requires continuous measurement and analysis, the physical model will be used to better understand the discrepancies and deviations of the physical system from predicted computer based modeling results.

The physical model requires both a data acquisition system and various sensors to test water quality and hydraulic flow characteristics. The network design includes pressure sensors, electrical conductivity sensors, flow meters, and tank meters. This report details the design, selection, and construction of the physical model and associated data acquisition and sensor components.

MODEL SKELETONIZATION

The first step in the design of the physical model was to skeletonize the schematic of a mid-size water distribution system. As a partner is this project, Nicholasville's water distribution system is the basis of the skeletonization. The goal of skeletonization is to reduce the network components required within the computer and physical model while preserving the hydraulic characteristics of the larger system. Figure 1 illustrates the full schematic of the system. This system was developed in KYPIPE, a widely accepted pipe network analysis program.

The system was skeletonized by deleting all pipes less than 10 inches in diameter and dead ends. The simplified model maintains the main loops and components of the system, including the three elevated storage tanks, pump station, and reservoir, which represents Nicholasville's water treatment plant. In the KYPIPE program, any water being drawn from the system is represented as a point load demand at a junction node. All the non-skeletonized system demands were aggregated so that the flow to any branch of the system was replaced by an equivalent demand. This maintained total system flows. Figure 2 shows the skeletonized system from the KYPIPE model. The system was reduced from 6,549 pipes and 6,218 junction nodes in the complete model to 27 pipes and 19 junction nodes in the skeletonized model.

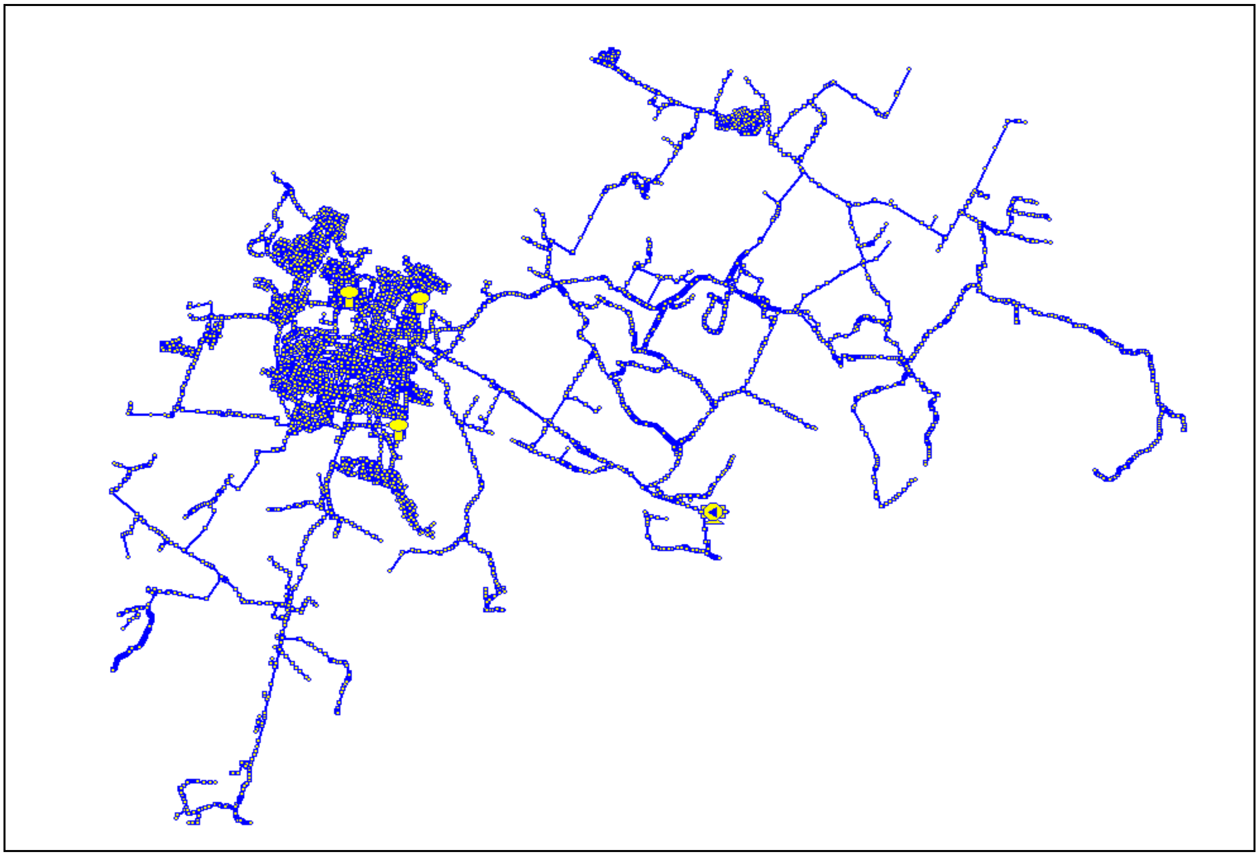

Figure 1: Nicholasville schematic

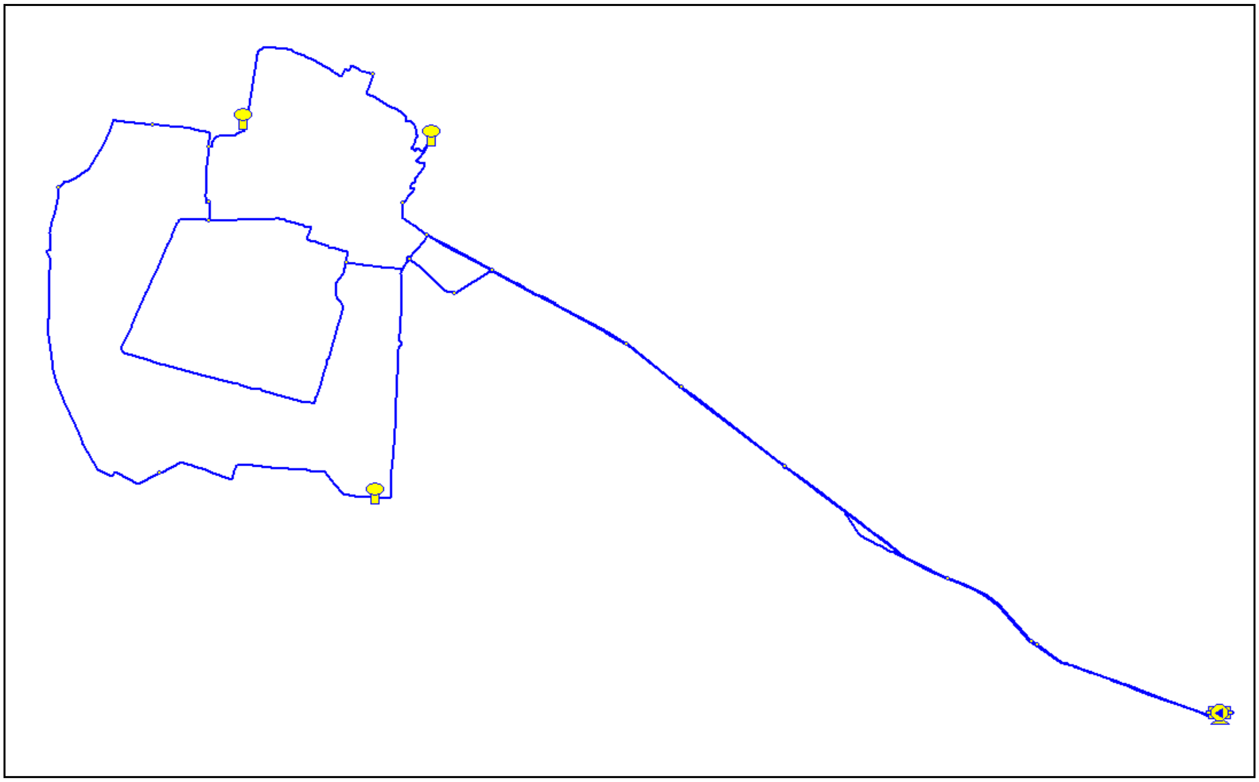

Figure 2: Skeletonized system

MODEL SCALING

When scaling the skeletonized system, the main objective was to preserve the mixing and hydraulic characteristics of the physical system. One constraint on the design was the physical space limitations within the hydraulics lab at the University of Kentucky. The initial goal was to scale the prototype by length, head loss, and travel time simultaneously, while maintaining turbulent flow throughout the system. This would give the greatest representation of fundamental parameters pertaining to the mixing properties of the prototype to the model. However, it quickly became apparent during the design that this would not be possible to scale simultaneously. For example, a 10 inch diameter pipe in the prototype scaled down by a factor of 10 would give a one inch pipe in the model. If that pipe were 3,000 feet long in the prototype, then it would be 300 feet in the model in order to maintain true length scaling. However, the hydraulics lab is approximately 60 feet long, which would mean that that pipe alone would span the entire length of the lab five times. This is not necessarily problematic until the energy losses due to friction was introduced and scaled into the system. Energy losses due to friction are a nonlinear function of flow and diameter. To keep the head losses proportional to the prototype, the length of each pipe in the model was adjusted. This in turn alters the length scaling. This constraint becomes even more exacerbated when travel time scaling is introduced.

Because of these challenges, we decided to scale primarily based on maintaining a constant ratio of travel time scaling. In other words, the time that the water takes to flow the length of any pipe in the skeletonized prototype will be scaled down by a constant for that same pipe in the model. This scaling was achieved by the following methodology.

The diameters were first approximately scaled by a factor of 10. That is, every pipe diameter in the prototype was divided by 10, and then rounded to the nearest commercially available pipe size (i.e. 1 inch, 1½ inch, and 2 inch). From the Darcy-Weisbach equation for friction energy losses, the following relationship between model and prototype was derived, with the subscript *p* indicating the prototype and *m* indicating the model.

$$\frac{L_p}{L_m} = \left(\frac{h_{fp} D_p f_m}{h_{fm} D_m f_p}\right)^{1/3} S_t^{2/3} \qquad \text{Eq. 1}$$

Here S_t is the scale factor for travel time, or $\frac{t_p}{t_m}$, which ultimately became equal to 300. The friction factor terms came from Nikuradse's equation for fully turbulent flow conditions:

$$\frac{1}{\sqrt{f}} = -2log\left(\frac{\varepsilon}{3.7D}\right) \qquad \text{Eq. 2}$$

The roughness height, ε, was estimated to be 10^{-5} feet for the prototype (which is primarily aged cast iron), and 10^{-7} feet for the model (which is new PVC). In order to utilize the relationship for the ratio of the lengths, it was necessary to find the corresponding head loss associated with that particular pipe. This was done by creating a KYPIPE model of the skeletonized prototype and lab model. Using an initial scale factor for all the pipes lengths, simulations were run with KYPIPE. This gave head loss estimates for both the prototype and the lab model; the lab model results were preliminary. The information was then used to obtain an updated length for each pipe in the lab model, and the simulation were updated and run again. This was done in an iterative process until there was no longer a change in the length or head loss between simulations.

The next step was to find the required flow through the system in order to keep the residence time scale factor true as well as maintain turbulent flow (Re> 5,000) throughout the system. Another important consideration was that the pressure everywhere in the model had to be greater than atmospheric pressure to ensure that the model would be able to operate as a pressurized system with specific outflow at the demand points. The magnitude of the nodal demands dictates the total flow through the system, in turn influencing the pressure at each junction. If there is too high of a demand at a node, then the pressure tends to drop to a point that is too low to provide the energy necessary to provide the specified flow at the demand point.

In order to find the appropriate demand flow rates for the model, they were first estimated and input into the KYPIPE model of the lab network. The Reynolds number was then calculated for each pipe to check whether the flow was turbulent. To scaled the flows based on travel time, the following relationship was derived using the mass balance equation, Q = VA, for steady state conditions.

$$Q_m = Q_p S_t \left(\frac{L_m}{L_p}\right)\left(\frac{D_m}{D_p}\right)^2 \qquad \text{Eq. 3}$$

Each KYPIPE computed pipe flow value was checked with the calculated flow from equation 3. In this equation, L represents the pipe length, D represents the inner diameter of the pipe, and S_t represents the theoretical global scale factor for travel time. The travel time was checked against the scale factor by creating an error term between S_t and the ratio of travel time for each pipe. Since the travel time of the model, t_m, is a function of pipe length, it can be adjusted by changing the pipe length until $\frac{t_p}{t_m}$ matches S_t.

$$\epsilon = \frac{t_p}{t_m} - S_t \qquad \text{Eq. 4}$$

The sum of the squared error terms from equation 4 was then minimized by adjusting the length of each pipe. Every time the error was minimized, another KYPIPE simulation was run to find updated flow rates, therefore updating the travel time of the corresponding pipe. Using this method, the lengths were adjusted to most accurately reflect a scaled travel time. Appendix B shows a table of the length, diameter, head loss, and Reynolds number for each pipe in the fill size and scaled models.

PHYSICAL CONSIDERATIONS

The pipe network operates similar to the real system. It contains a reservoir that acts as the source, a pump to supply the system with the appropriate power to maintain pressure and flow, and three elevated storage tanks that can be filled or drained depending on the conditions set by the operator. There are gate values at each demand point and at the pump for flow adjustment. There are ball valves at the midpoint of each pipe to allow for model calibration and to cut flow to different sections of the model for different simulations.

Before constructing the network, the system requires structural support. This structure needs to be able to hold all the elevated components of the system, namely the pipe network and the elevated tanks when full. Also water is to constantly circulate through the system, which means there must be return lines to the supply reservoir. Besides the outflow(s) representing water usage by consumers, another potential outflow location is the elevated tanks. In the event that they overflow, a bypass is placed to collect the overflow and return it to the reservoir. Hence, a return system has been implemented in order to maintain a conservative system.

SUPPORT STRUCTURE

The physical model was designed to fit within the space limitations of the hydraulics lab. To accomplish this we built the system in a vertically laid configuration. The system was designed to hold the majority of the pipes on two aluminum trays, one above the other, each spanning 60 linear feet across the lab. Both trays are supported by ½ inch threaded steel rods held up by steel angle brackets. These 11 brackets are placed approximately six feet apart, spanning the entire length of the lab. They are anchored into a reinforced concrete beam using ¼ inch anchor bolts. The lower aluminum tray is nine feet above the floor of the lab, where the supply reservoir is located, with the upper tray sitting two feet higher. The model is accessible from the laboratory sedimentation flume walkway. Since the prototype contains three elevated storage tanks, the model also has three tanks, each one resting on a platform that is secured to the reinforced concrete beam. All elevated tanks are 17 feet above the floor. Figure 3 shows the configuration of the trays with a platform for one of the tanks.

Figure 3: Pipe support structure with tank platforms

Figure 4: Pipe configuration

PIPE CONFIGURATION

The network of pipes rests on the aluminum tray structure as support, as seen in Figure 4. Some of the pipe lengths in the computer model are longer than the 60 foot length of the trays, so a 180° bend was used to give room for additional length. A corresponding minor loss coefficient was then added to the computer model to represent the energy loss through the bend. The overall length of pipe was adjusted to maintain the proper scaling. In order to place the pipes in the correct configuration, a schematic was drawn using AutoCAD. The schematic can be found in Appendix A.

The system was constructed with 10 demand nodes spread throughout the model, each of which is simulated using a tee. Each tee has a 90° elbow with a one inch diameter pipe segment running parallel to the aluminum tray. Each one of these outlet points contains a flow meter with a 10 inch segment of pipe on each side. A gate valve was placed on the downstream side to control the flow. Immediately downstream of the gate valve, another elbow is put in place to turn the pipe downward toward a return line. The user has the ability to fine-tune the flow while constantly monitoring it to ensure the correct demand at each outlet. Figure 5 shows the configuration of two different outflow points being fed into the return line. The line being fed into the left pipe in the photo is located on top of the tray, whereas the other one is from the bottom tray.

There are two return lines in the model, each of which transmits water back to the reservoir from the outflow locations and the tank overflow pipes. The return lines are six inch diameter PVC pipes that hang directly below the aluminum trays using pipe hangers. They have a series of tees, each with a 2 inch or 3 inch vertical pipe to collect water from a demand (discharge) point. Each discharge pipe is extended about four inches into the larger return pipe. This allows for the return line to be gravity-driven rather than being pressurized.

Figure 5: Discharge node configuration into the return line

RESERVOIR CONSTRUCTION

The reservoir supplies water to the system, so it must be able to hold enough water volume to fill the system entirely. Furthermore, it needs to have a minimum depth of a foot and a half in order to adequately submerge the intake (suction) line of the pump. This brings the total volume to approximately 900 gallons.

The reservoir was built using treated 2×6 studs and ¾” treated plywood to form a 9’10” (L) × 2’0” (W) × 6’3” (H) box. The 2×6 studs were placed one foot on center with the plywood fastened using galvanized screws. A 6-mil plastic liner covers the inside walls to maintain a water-tight reservoir. The inlet pipe of the pump goes through the wall of the reservoir via a bulkhead fitting and is turned downward with a 90° elbow. This was done to reduce potential for vortex formation in the reservoir.

The pump is a three horsepower Grundfos model CR 20, which has a rated flow of 102 GPM with a rated head of 52.8 feet. The discharge line of the pump is two inches in diameter and is equipped with a gate valve. Using a gate valve allows for fine-tuned adjustment of the flow and head to accurately model smaller or larger demand patterns of up to about 1.5 times the initial estimated demand.

Keeping with the notion of being able to run multiple simulations with the physical model, a ball valve has been installed in every pipe. This will allow the operator to turn any pipe on or off independently, giving the operator the freedom to set up multiple configurations and calibrate instruments and pipe loop sections.

DATA ACQUISITION AND SENSOR SYSTEM INTRODUCTION

The research objective for this portion of the project is to develop both a physical and computer based water distribution network model. The ultimate goal is to gain an understanding of the limitations and discrepancies of the computer modeling when simulating a physical distribution model. To do so requires the ability to continuously monitor the parameters (flow, pressure, and containment concentration) within the system. This required the use of sensing equipment, along with a data acquisition system, to transfer the analog current loop information into digital information for computer processing and analysis.

The data acquisition system has a total of 44 sensors (15 flow meters, 19 pressure meters, 4 tank meters, and 6 electrical conductivity meters). The 19 pressure meters have been placed at each junction and at each tank base within the physical system. There are 4 water level meters for the reservoir and 3 water tanks. The minimum number of flow meters required for the system was 15 flow meters: 3 for the pipes to the tanks, 2 for the transmission lines, and 10 for each of the demand points in the skeletonized design. The 6 electrical conductivity meters have been placed throughout the network. There are 12 uniformly distributed ports for measurement in the system, which will allow for some flexibility in water quality measurements.

4-20 MA CURRENT LOOP

The primary constraint on sensor selection was the length of cable required (over 60 feet). The selected sensor instruments operate on the 4-20 mA current loop principle due to the measurement lengths required. The sensor device operates as a variable resistance element in a closed loop supplied with 20 mA of current. The force of the phenomenon measured (flow, pressure, etc) is transferred to electric resistance by onboard electronics or by turning a regulator within the instrument. The higher voltage required to power the instruments (10-30 DVC typically) are converted to a 5 V resistance at the data acquisition module as a safety to protect the data acquisition module from high temperatures and transients. The data acquisition module converts the analog DC currents to AC current, and via a multiplexer, converts the information to digital input a PC can translate and analyze.

The advantages of a current loop design principle for data collection are: long distance transmission without amplitude loss, inexpensive two-wire cables can be used since voltage losses are less problematic and lower sensitivity to EMI (S. Sumathi 2007, 245). A current loop requires two current inputs to a data acquisition system. This halves the number of sensors that can be examined on a single card or module. A smaller pulse based sensor operates using a much simpler principle of counting the frequency of a number of switch turns on the instrument utilizes one input into the data acquisition system. Unfortunately, they are limited to very short distances of about 10’ without a signal conditioner. This, in turn, reduces or eliminates the economical advantage.

Figure 6: National Instruments modular data acquisition unit

DATA ACQUISTION DESIGN ALTERNATIVES

Three design alternatives of data acquisition systems produced by three design manufacturers were considered for the data acquisition needs of the research project. The DATAQ model utilizes modular integrated 32 differential current signals units. The modular self-contained units can be combined together simply by daisy chaining multiple units with standard CAT 5 cable. There is no internal expandability in DATAQ model, since they are self contained units. The Omega system and the National Instruments system are both similar and utilize an expansion card in expandable open chassis design. The primary difference being that the National Instruments system has an onboard module for transferring the data to a PC via Ethernet connection whereas the Omega System utilizes a separate module. The final selection was for a National Instruments system. The decision on the unit was based primarily on price, since the units have similar technical specifications. After various discounts, in particular a significant discount on the Lab VIEW software, the final system was purchased for $4,177.83 (Figure 6). This 9208 module cards are single ended measurements where one terminal of the amplifier is tied into the instruments positive line while the negative terminal of the amplifier is tied in a natural ground line. Single ended measurements are referential measurements to a common ground.

DATA ACQUISTION SYSTEM FEATURES & SPECIFICATIONS

Detailing the performance characteristics of the data acquisition system requires some theoretical aspects of signal processing. The input signals from the sensors are scanned, amplified, conditioned, and sampled by a single 24 AC/DC converter. The power support for the data acquisition module chassis can be made with a standard wall outlet by an extension cord. However, a 16 AWG or larger gauge connection to an earth ground is required. The sensors are protected by the single 24 AC/DC converter, plus or minus 30 V. However, only the currently scanned loop can be overprotected. This power connection supports the module and data conversion, but the individual loops and sensors must be supplied by a separate power source.

Each of the four NI 9208 cards can sample at rate up to *500 S/sec*; this works out to approximately *30* samples per seconds for each of the *16* sensors wired to each card. However, the *30* samples maximum must be processed by the multiplexer and controller on the chassis into AC current and then digital information using the following equation:

$$\tau_o = n \times \left(T_q + t_{Delay} + t_{Conv}\right) \quad \text{Eq. 5}$$

where

$n = Number\ of\ instruments$

$T_q = Quantization\ resolution, time\ resolution\ in\ multiplexer$

$t_{Delay} = Time\ delay\ to\ clear\ the\ channel\ between\ conversions\ in\ dif\ sensors$

$t_{Conv} = Frequency\ conversion\ time\ from\ DC\ current\ from\ sensor\ to\ AC\ into\ computer$

The data acquisition chassis can convert the samples at two rates. In high resolution mode, the conversion time is *52 ms* per channel with an additional *10 µs* settling time between channels. The quantization time (minimum time resolution) is *12.5 ns*. For *44* instruments, this works out to approximately *0.437* samples per second per instrument using Eq 5. In high speed mode, the conversion time is *2 ms* per channel with an additional *10 µs* per channel of settling time between channels. At high speed mode this works out to be *11.36* samples per second. The chassis has the ability to setup three task groups. Each task group can be setup to run at different sample rates by splitting the clock speed differently. Sensors on the same NI 9208 card must be in the same task group, they cannot be split into separate task groups.

ELECTRICAL CONDUCTIVITY DESIGN CONSIDERATIONS

When consider an artificial uniform box of water as a control volume of a larger quantity of water, the water has an indeterminate amount of molecules of various substances either dissolved or floating within the uniform volume of water. If two electrical plates are placed on two parallel faces of the uniform box of water of given length *L* and frontal area *A*, and a battery of constant voltage connected to the two plates, the current running between the two plates will be a function of both the resistance of the water and the molecules of various substances and/or dissolved materials in the liquid and of course the voltage of the battery. An alternating voltage can be used to prevent hydrolysis or a stainless steel probe can be used to prevent hydrolysis. Hydrolysis is the process of using electricity to power a chemical reaction. Using a constant voltage can change the chemical components within the liquid and induce errors in the measurement.

The current will decrease as the resistance increases. The total resistance will increase as the length between the probes/plates increases and more current can be conveyed as you increase frontal area of the plates. Resistance for a uniform specimen of material for a unit length can be written in a form called electrical resistivity. The electrical resistivity for a uniform material or substance is a constant value for a constant density (pressure and temperature constant) for a given unit of length. For the case of stationary plates (or near stationary plates) and a flowing liquid or gas, it also varies with viscosity of the flowing liquid or gas, given as

$$\rho = R\left(\frac{A}{L}\right) \qquad \text{Eq. 6}$$

where

$\rho = electrical\ resistivity, Ohms - meter\ \Omega \bullet m$

$A = Area\ of\ probe, plate\ in\ sq\ meters$

$L = distance\ between\ two\ plates/probe\ in\ meters$

The inverse of electrical resistivity is the electrical conductivity. A high electrical conductivity indicates a low resistance to electrical current traveling through the substance. The following equation describes the relationship.

$$\sigma = \frac{1}{\rho} = \left(\frac{L}{AR}\right) \qquad \text{Eq.7}$$

where

$\sigma = electrical\ conductivity, \frac{Siemens}{meter}\ ; \frac{S}{m}$

Most handheld voltmeters can measure electrical resistance and thus can measure electrical conductivity (although crudely). The selected instruments utilized for the experimental apparatus have a single high precision probe and are integral to the data acquisition for continuous measurement. The instrument (GF Signet 2850) measures resistivity and electrical conductivity will be determined by dividing by the cell constant for the electrode.

CONTAMINANT TRACER BACKGROUND

To perform testing that simulates the flow dispersion and spread of a contaminant within the physical model requires utilizing a tracer of some variety. The selected tracer for the experiment will be solutions of calcium chloride salts. Calcium chloride is a high-reactivity substance within water. In addition highly purified calcium chloride is available commercially at low prices.

Table 1: Molar conductivity for dilute ½$CaCl_2$ solutions

concentration (mol/L)	Λ (molar conductivity 10^{-4} Siemens/mols)	Λ 1/2 $CaCl_2$
Infinite dilution	135.77	271.54
0.0005	131.86	263.72
0.001	130.3	260.6
0.005	124.19	248.38
0.01	120.3	240.6
0.02	115.59	231.18
0.05	108.42	216.84
0.1	108.41	216.82

Calcium chloride solutions will be used as the tracer through the physical model for water quality modeling. An important consideration is the model will be using potable water from the laboratory supply while the references values for calcium chloride from the literature are for calcium chloride solutions using pure water. Much of the literature on electrical conductivity for solution is geared toward a chemical engineering perspective, hence referenced to pure water. Therefore, there will be a background level of electrical conductivity within the model, and in addition, the molar conductivity will vary from the presented values presented for pure water and calcium chloride solutions from the literature. Measurement and calibration of EC measurements to various concentrations of solution concentration will be developed using laboratory water. Table 1 gives the relationship between concentrations and conductivity.

ELECTRICAL CONDUCTIVITY SENSORS

The selected electrical conductivity sensors are GF Signet 2850 Conductivity/Resistivity Sensors (Figure 7). The factory calibrated 1.0 cell constant can measure conductivities in the range is 0 to 10,000 µS/cm. (Georg Fischer Signet LLC 2006).

There are two forms of inaccuracy with the device. The current output can be $\pm 2\%$ of the range. This refers to a slight inaccuracy from translating the resistance loss in the 4-20 mA current loop for measurement by the data acquisition system. The device measurement will thus be $\pm 200\ \mu S/cm$ from the discrepancy between reported and true electrical conductivity results. This is a constant error. In addition there is a slight variability in the cell constant due to production tolerances in the geometry of the electrodes length to area relationship. This translates to an additional $\pm 2\%$; however it is possible to obtain an electrode with a lower production tolerances of $\pm 1\%$ which was done for the project. During ordering, the special ordered electrode was specified in the purchase order to maximum accuracy. This error is non-constant, because it represents the production tolerance on the geometry of the probe and is at its worst at the higher end of the spectrum. The resistivity is divided by the cell constant to obtain the electrical conductivity measurement and so the error in the instrument L/A ratio implies a measurement will be off by *99%* or *101%* of the true measurement plus or minus the constant $\pm 200\ \mu S/cm$. The maximum error will thus be $\pm 300\ \mu S/cm$.

Figure 7: GF Signet 2850 conductivity/resistivity sensor & 2821 electrode[1]

The six electrical conductivity sensors will be placed in twelve random sampling locations within the simulated physical model. The locations were determined by qualitatively looking at the water distribution computer model and identifying twelve locations that would give the widest coverage through the network.

ELECTRICAL CONDUCTIVITY CONSTRUCTION CONSIDERATIONS

The primary concern with assembling the electrical conductivity meters in the physical scale model was connecting the instrument's ¾ inch NPT male threaded fitting to the non-threaded 1 inch and 1.5 inch pipes. Since the majority of the pipes within the network are 1.0 inch or 1.5 inch, a connector bushing were purchased and added at the pipe tees where the electrical conductivity meters were installed. The probe length of the model is 1.65 inches, the pipe tee and connector bushing was measured to insure that the adequate room was available between the connector and tee neck without the probe intruding into the main flow area. The natural length of the connector bushing and tee neck was of a sufficient length for the probe as not to intrude into the mean flow.

FLOW METER SENSOR DESIGN CONSIDERATIONS

Flow measurement can be made in a variety of different methods. In turbine flow transducers, the force of flow is translated into a voltage resistance measured on current loop. Flow transducers are the most popular way of measuring flow in a process control environment. (Omega Systems n.d.).

The turbine-paddlewheel flow transducer can also be setup as a pulse output device inside of a current loop. A pulse or relay output devices operate as a "switch" essentially on a circuit between a battery and current measurement device. One turn of the wheel turns the switch on/off; the time between of switch turns translates to frequency of current wave on the output line which indicates the flow rate. A pulse/relay based turbine and paddlewheel meter is the most economically option available for flow measurement. However, pulse flow meters are limited to a very short distance (typically 10 ft.) otherwise the resistance losses in the wire significantly affect the accuracy of measurement due to

[1] Image reproduced from Instrumart Website. Copyrighted G.F. Signet

frequency distortion. This can be overcome with a signal conditioner; however this creates additional expense and makes a turbine paddlewheel designed on measuring the voltage resistance in a current loop a more economical selection.

However, a turbine paddlewheel creates an additional system loss in the energy equations of flow. This is a bigger problem because the energy losses for the unit (K factor * velocity head), are typically not tested or referenced by the manufacturer. This is due to the losses being insignificant in the context of primary usage of the instruments in process control applications and other distribution system to other forms of energy losses. However the energy losses are significant in the scaled model in reference to the full sized system. In addition, the blade creates a surface were corrosion can occur and/or residue from one contaminant test run can add uncertainty to the proceeding test run and act to change the mixing properties.

A design decision was thus made based on these considerations to use a nonintrusive Doppler transit flow meter. Ultrasonic sound is transmitted into a pipe with flowing liquids and the discontinuities reflect the ultrasonic wave with a slightly different frequency that is directly proportional to the rate of flow of the liquid (Omega Systems n.d.). About *100 PPM* (parts per million) are required of suspended solids to reflect the ultrasonic waves. The laboratory environment and tap water utilized in the laboratory will meet the suspended solids criterion. Flow meters were placed in the two transition lines, the three tank lines, and the eight demand points of outflow of the physical model.

FLOW METER CONSTRUCTION CONSIDERATIONS

The flow meters operate best in a horizontal orientation. Thus all the flow meters with the exception of the tank flow meters were placed in the horizontal orientation. The inline brass flow meters had NPT pipe threaded connections and required adding a threaded to non threaded PVC pipe connector. Additional brass pipe sealant was purchased for connecting the brass inline flow meters to the PVC threaded to non threaded connectors.

PRESSURE SENSOR DESIGN CONSIDERATIONS

The pressure sensors utilized in the project are force transducers. As described previously, force transducers translate force measurements into current voltage measurements that can be digitalized through a data acquisition system or chart recorder. The selection of pressure measurement devices was made on a cost and accuracy comparison. Pressure transducer units are more standardized across the process control industry than other flow distribution measurement devices. The pressures within the physical model are under 30 psig. The pressure sensors were ordered from Clark Solutions (Figure 8). Four surplus pressure meters were purchased due to past experience with durability issues with pressure transducers.

Figure 8: Clark Solutions Noshok Series 100 pressure transducers[2]

PRESSURE SENSORS CONSTRUCTION CONSIDERATIONS

The pressure meters have a ¼ inch NPT thread connection for insertion into the physical model. A ¼ inch hole will be drilled into the 1 inch PVC pipes near the junctions were pressure measurements are required. The pressure transducer will then be inserted into the drilled hole and secured with silicon pipe sealant.

TANK LEVEL DESIGN CONSIDERATIONS

Three types of tank level measurements were considered for measuring the tank levels in the physical model. Water level measurement can be achieved in three manners. The first manner is to consider using a pressure sensor at the bottom of the tank to measure pressure resulting from the water height above the tank. A second method is to utilize a mechanical float that moves up and down a metal rod. Wires within the metal rod carry a very small positive and negative current and the circuit is closed at the float. The measured resistance in the loop corresponds to the height of the float at the water's surface. A third method was to utilize an ultrasonic Doppler transmitter similar to the Doppler flow meter that utilizes the Doppler shift to determine the distance between the transmitter and the object surface (water) the signal reflects. The mechanical flow meters were ruled out as viable alternatives due the relatively high expense and the relatively high resolutions limitations. A Doppler level meter was

[2] Image reproduction, Clark Solutions website. Image copyrighted Clark Solutions

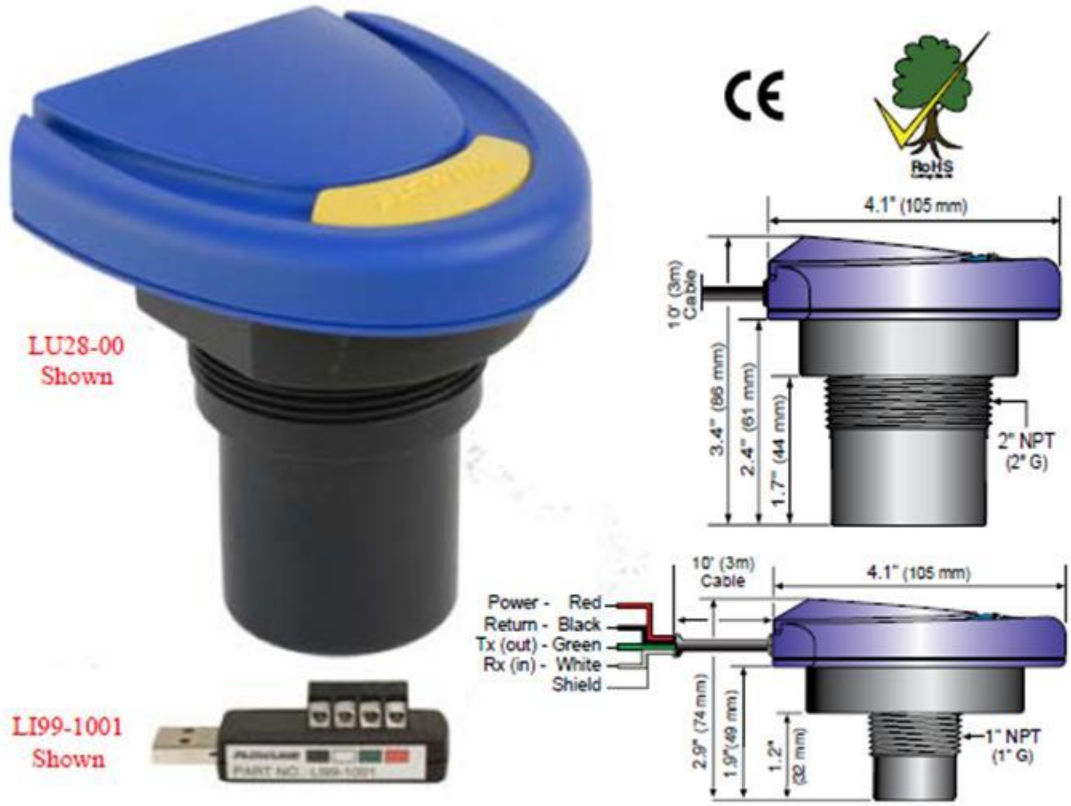

Figure 9: Flow Line Echosonic II Doppler level meter[3]

chosen (Figure 9) over the pressure meter despite the higher costs, due to the higher accuracy levels. One issue that could prove to be problematic during testing is wave action in the tanks as they are filling and emptying during a modeled simulation. The four additional pressure meters purchased as surplus can be used if wave action in the tanks becomes problematic during laboratory testing during some tank filling simulations. The wave action issue will not be a problem with the larger reservoir tank, only the smaller volume tanks.

WATER LEVEL METER CONSTRUCTION CONSIDERATIONS

The water level meters have a 2 inch NPT fitting. The meters will be snuggly inserted in the top of the physical model tanks via drilled holes in the plastic tanks. The level meter at the wood construction reservoir will be inserted in through a drilled hole in wooden plank, and/or via a bulkhead fitting.

[3] Image reproduction, Instrumart website. Image copyrighted Flowline

Figure 10: McMaster-Carr fine-adjustment diaphragm injection pump

INJECTION PUMP DESIGN CONSIDERATIONS

The injection pump that will serve to release the contaminant into the system will be a McMaster-Carr Fine Adjustment Diaphragm Metering Pump. The injection will take the calcium chloride solution via a 5/16 inch input and inject the solution into the physical model via a 3/8 inch discharge tubing line. The injection pump will be supported on a movable tray that will allow multiple staging areas/locations into the physical system. The flow rate the pump can produce is 100 gallons/day against a maximum back pressure of 60 psig. A brass check value will be added to ensure that there is no backflow.

ELECTRIC WIRING DESIGN CONSIDERATIONS

The sensors will be supplied by a single adjustable DC power supply. A Mastech 30 volt, 3 ampere adjustable DC laboratory power supply will supply power to each of the sensors current loops. The wire and splicing will be done with 16 gauge 3 conductor wire. A ground line will be installed throughout the physical model. An earth ground line will also be supplied at the data acquisition system. The power supply after passing thru a *2 ampere* fuse will plug directly into the *4* card modules. The 4 card modules will supply voltage to the sensors thru the *16 V* up channels; the negative terminals of the sensors will plug into the module cards *16 A* channels. The power supply, sensors, and data acquisition will all be referenced to the common earth ground to minimize signal noise.

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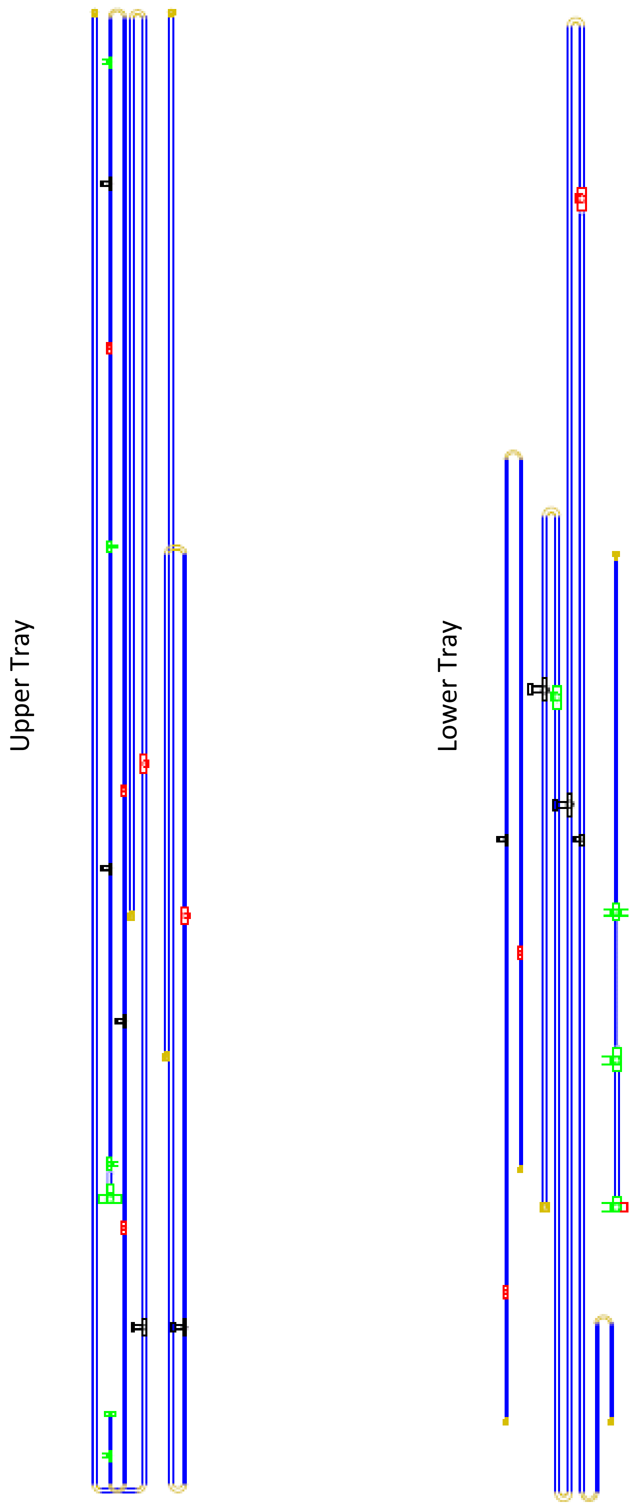
APPENDIX A: PIPE SCHEMATIC



APPENDIX B: SCALING RESULTS

	Full-Size				Scaled			
Pipe	**Length (ft)**	**Diameter (in)**	**Head loss (ft)**	**Re**	**Length (ft)**	**Diameter (in)**	**Head loss (ft)**	**Re**
P-1	111.51	12	0.060	87797	1.89	1	0.230	37296
P-2	1242.09	10	2.740	134345	11.31	1	1.310	36688
P-3	816.00	10	0.010	8335	25.69	1	0.160	7873
P-4	1894.04	10	10.270	218160	15.53	1	3.430	53680
P-5	2377.93	10	1.620	71243	11.70	1	0.160	10517
P-6	4673.00	10	0.810	33916	50.26	1	0.670	10943
P-7	7598.37	20	0.030	14494	21.25	1	0.004	608
P-8	15089.27	20	2.130	94057	107.44	2	0.470	20092
P-9	3621.19	10	0.050	8778	75.65	1	0.130	5502
P-10	3629.53	10	1.110	46257	10.73	1	0.030	4103
P-11	7380.44	20	4.620	210496	51.49	2	1.000	44059
P-12	21.75	20	0.030	323745	0.15	2	0.010	66963
P-13	323.42	20	0.060	113249	2.18	2	0.010	22904
P-14	2625.82	12	1.900	113162	16.61	1.5	0.270	24743
P-15	6183.48	16	20.040	355445	41.60	1.5	4.190	67257
P-16	13812.92	12	47.200	261424	101.33	1.5	9.940	66284
P-17	1207.46	20	1.770	333274	8.38	2	0.370	69410
P-18	1271.02	10	3.690	155675	7.95	1	0.600	29211
P-19	109.33	20	0.020	116439	0.75	2	0.005	23952
P-20	47.51	12	0.070	147166	0.62	1	0.130	47813
P-21	51.53	10	0.140	151717	0.23	1	0.010	20457

P-22	22.07	10	0.030	97837	0.29	1	0.030	37904
P-23	9747.25	12	21.540	206632	73.82	1.5	4.970	54085
P-24	13893.11	16	48.730	370985	95.22	1.5	10.750	71512
P-25	2317.35	10	5.740	142939	14.03	1	0.850	25958
P-26	56.87	36	0.010	259431	0.60	2	0.010	68898
P-27	79.72	24	0.090	389147	0.38	2	0.005	68898

APPENDIX C: MATERIAL LIST

Support Structure

Part	*Vendor*	*Item #*	*Qty.*	*Price*	*Total*
12' Cable Trays	McMaster-Carr	30065T413	10	$202.85	$2,028.50
Angle Brackets	McMaster-Carr	2971T13	11	$84.85	$933.35
Steel Perforated Tubing	McMaster-Carr	6535K35	11	$31.28	$344.08
Anchor Bolts	McMaster-Carr	92403A300	22	$2.16	$47.52
Washers	McMaster-Carr	91081A131	100	$0.05	$4.89
Nuts	McMaster-Carr	90473A031	100	$0.05	$4.86
C4x4.5x4' Channel	Mid-State Steel		1	Free	Free
12Gx2"x19" Sheet	Mid-State Steel		22	Free	Free
Washers	McMaster-Carr	98026A033	1(25/Pack)	$7.14	$7.14
Steel Threaded Rods	Grainger	4FGR9	22	$9.19	$202.18
Washers	Fastenal	11103740	1 (25)	$39.00	$39.00
Steel Perforated Tubing	McMaster-Carr	6535K39	3	$43.97	$131.91
3/8" Anchor Bolts	McMaster-Carr	92403A203	14	$2.01	$28.14
Masonry Drill Bit, 5/16"	McMaster-Carr	2899A27	1	$9.26	$9.26
Masonry Drill Bit, 3/8"	McMaster-Carr	2899A31	1	$9.99	$9.99
Hex Bolts	McMaster-Carr	92865A638	10	$7.32	$7.32
L-Bracket	McMaster-Carr	1556A36	12	$0.71	$8.52
I-Beam Clamp	McMaster-Carr	1815T11	1	$7.56	$7.56
Expansion Shield Anchor	Fastenal	51131	26	$28.26	$28.26
Bolts	McMaster-Carr	91309A546	100	$9.21	$9.21
Bolts	McMaster-Carr	91309A551	25	$4.13	$4.13
Clamps	McMaster-Carr	1815T11	3	$7.56	$22.68
Board	Home Depot	809209	3	$4.72	$14.16
3/4x4x8 Plywood	Home Depot		1	$10.00	$10.00
1/4" Anchor	McMaster-Carr	97046A131	8	$9.48	$9.48
1/4" Drill Bit	McMaster-Carr	2899A25	1	$7.58	$7.58
Anchor Bolts	McMaster-Carr	97046A131	1 (25)	$9.48	$9.48
1-7/8" Hole Saw	Lowe's	348106	1	$10.48	$10.48
3-1/4" Hole Saw	Lowe's	348147	1	$21.97	$21.97
4-1/2" Hole Saw	Lowe's	348153	1	$39.97	$39.97
6" Hole Saw	Lowe's	348123	1	$39.96	$39.96
Hole Saw Arbor	Lowe's	300697	1	$19.68	$19.68
				Subtotal:	**$698.06**

Tanks

Part	*Vendor*	*Item #*	*Qty.*	*Price*	*Total*
110 Gal Storage Tank	Gempler's	147668	3	$168.00	$504.00
1" Bulkhead Fitting	McMaster-Carr	36895K123	2	$17.02	$34.04
2" Bulkhead Fitting	McMaster-Carr	36895K126	1	$32.52	$32.52
2" Bulkhead Fitting	Grainger	3CEF8	2	$30.30	$60.60
3" Bulkhead Fitting	Grainger	3CEG5	1	$55.60	$55.60
				Subtotal:	**$686.76**

Pumps

Part	*Vendor*	*Item #*	*Qty.*	*Price*	*Total*
Grundfos CR-20 Pump	D&F Distributors	96524008	1	$1,812.00	$1,812.00
Flange Gasket	McMaster-Carr	9472K45	2	$3.82	$7.64
2" PVC Flange	Ferguson Enterprises	PFP80VSSFK	2	$6.48	$12.96
Diaphragm Metering Pump	McMaster-Carr	4233K54	1	$431.67	$431.67
Clear PVC Tubing	McMaster-Carr	5231K355	25	$0.42	$10.50
Brass Check Valve	McMaster-Carr	7768K14	1	$19.83	$19.83
Cord	Kentucky Lighting & Supply, Inc	28758	147	$1.50	$220.63
1/2" Cord Grip	Kentucky Lighting & Supply, Inc	158809	1	$1.51	$1.51
3/4" Cord Grip	Kentucky Lighting & Supply, Inc	158811	1	$2.00	$2.00
4-Wire Connector	Lowe's	197500	1	$25.37	$25.37
4-Wire Plug	Lowe's	197496	2	$17.13	$34.26
				Subtotal:	**$2,578.37**

Pipes

Part	*Vendor*	*Item #*	*Qty.*	*Price*	*Total*
1" PVC Gate Valve	McMaster-Carr	9762K43	12	$12.22	$146.64
2" PVC Gate Valve	McMaster-Carr	9762K46	1	$25.64	$25.64
1" PVC Ball Valve	Grainger	4YLH8	14	$6.21	$86.94
1.5" PVC Ball Valve	Grainger	4YLJ1	5	$13.01	$65.05
2" PVC Ball Valve	Grainger	4YLJ2	6	$19.64	$117.84
1"x20' PVC Pipe	Ferguson Enterprises	P40BEPG20	14	$11.76	$164.64
1.5"x20' PVC Pipe	Ferguson Enterprises	P40BEPJ20	16	$13.65	$218.42
2"x20' PVC Pipe	Ferguson Enterprises	P40PM20	8	$17.17	$137.32

1" PVC Adapter	Grainger	6MV37	2	$5.09	$10.18
2" PVC Adapter	Grainger	6MV40	1	$12.30	$12.30
2"x1" PVC Bushing	Grainger	2PLU6	3	$15.91	$47.73
2"x1" Reducer Bushing	Grainger	2PLU6	3	$14.32	$42.96
6"x6"x4" PVC Tee	Lowe's	53347	8	$26.82	$214.56
6" PVC 90 Street Elbow	Lowe's	53231	2	$22.84	$45.68
6" PVC 90 Elbow	Lowe's	53037	2	$19.89	$39.78
3" PVC 90 Elbow	Lowe's	23354	1	$2.28	$2.28
2" PVC 90 Elbow	Lowe's	23353	2	$0.84	$1.68
4"x3" PVC Bushing	Lowe's	23313	3	$5.29	$15.87
4"x2" PVC Bushing	Lowe's	23314	12	$6.57	$78.84
2" Clear PVC Tee	McMaster-Carr	9161K36	2	$40.08	$80.16
1" Clear PVC Tee	McMaster-Carr	9161K33	2	$16.23	$32.46
PVC 45 Elbow	Lowe's	23337	2	$0.61	$1.22
PVC 60 Elbow	Lowe's	186900	1	$2.18	$2.18
1" PVC 90 Elbow (5)	Lowe's	26056	4	$2.16	$8.64
3/4" PVC Plug	Lowe's	23524	7	$0.95	$6.65
1.5" PVC 90 Elbow	Lowe's	23909	10	$1.20	$12.00
2" PVC adapter	Lowe's	23904	2	$1.20	$2.40
1"x3/4" PVC Bushing	Lowe's	23911	12	$0.82	$9.84
1"x10' PVC Pipe	Lowe's	23976	3	$3.24	$9.72
1"x20' PVC Pipe	Ferguson Enterprises	P40BEPG20	1	$11.76	$11.76
2"x20' PVC Pipe	Ferguson Enterprises	P40PK20	2	$17.17	$34.33
3"x20' PVC Pipe	Ferguson Enterprises	P40PM20	1	$36.57	$36.57
2" Bronze Gate Valve	Ferguson Enterprises	NT134K	1	$179.00	$179.00
Pivoting Steel Hanger	McMaster-Carr	3037T25	10	$6.03	$60.30
6"x10' PVC	Lowe's	86806	6	$38.55	$231.30
1" PVC Tee	Home Depot	401-010HC	11	$0.64	$7.04
1-1/2" PVC Tee	Home Depot	401-015HC	5	$1.60	$8.00
2" PVC Tee	Home Depot	401-020HC	8	$2.44	$19.52
1" PVC 45 Elbow	Home Depot	417-010HC	20	$0.87	$17.40
1-1/2" PVC 90 Elbow	Home Depot	406-015HC	15	$1.25	$18.75
1" PVC 90 Elbow	Home Depot	406-010HC	26	$0.48	$12.48
2" PVC 90 Elbow	Home Depot	406-020HC	10	$1.80	$18.00

1-1/2" PVC Cross	Home Depot	420-015HC	1	$3.51	$3.51
				Subtotal:	**$2,297.58**

Reservoir

Part	*Vendor*	*Item #*	*Qty.*	*Price*	*Total*
Steel Threaded Stud	McMaster-Carr	95412A644	8	$9.19	$73.52
Steel Washer	McMaster-Carr	98370A021	8	$7.89	$63.12
Steel Hex Nut	McMaster-Carr	93827A225	1	$11.89	$11.89
2x6 Lumber	Home Depot	168-746	25	$7.97	$199.25
4x8x3/4" Plywood	Home Depot	261-688	10	$29.97	$299.70
Wood Drill Bit	Home Depot	174-858	1	$2.98	$2.98
2" Exterior Screw	Home Depot	133-938	2	$8.47	$16.94
4" Exterior Screw	Home Depot	137-008	1	$8.47	$8.47
Silicone Caulk	Home Depot	362-646	2	$5.95	$11.90
Large Ratchet	Home Depot	692-835	2	$12.74	$25.48
6 Mil Plastic Sheet	Home Depot	938-971	1	$98.00	$98.00
G. Lag Screw 4"	Lowe’s		144	$1.70	$244.80
G. Lag Screw 3"	Lowe’s		44	$1.50	$66.00
G. Washer	Lowe’s		150	$0.55	$82.50
G. Carriage	Lowe’s		6	$1.45	$8.70
2"x4"x12' treated	Lowe's	77671	5	$4.97	$24.85
3/8" Hex nuts	Lowe's	63303	20	$0.12	$2.40
Liquid Nails	Lowe's	44906	5	$2.47	$12.35
4" Deck Screw, 1 lb	Lowe's	9487	2	$8.47	$16.94
Wall Plate	Lowe's	78967	1	$1.27	$1.27
Flat Washers	Lowe's	63310	16	$0.33	$5.28
Hex Lag Screws	Lowe's	63350	8	$0.24	$1.92
Hex Bolts	Lowe's	63381	8	$1.10	$8.80
2" Bulkhead Fitting	Grainger	3CEF8	1	$27.27	$27.27
				Subtotal:	**$1,314.33**

Data Acquisition

Part	*Vendor*	*Item #*	*Qty.*	*Price*	*Total*
cDAQ 9188	National Instruments		1	$1,259.10	$1,259.10
power cord	National Instruments		1	$8.10	$8.10
NI 9208	National		4	$494.10	$1,976.40

	Instruments				
CB-37F-LP Unshielded, I/O Connector Block	National Instruments		4	$35.10	$140.40
SH37F-37M-1 37-pin Female to Male shielded I/O Cable 1m	National Instruments		4	$26.10	$104.40
LabVIEW Full Development System, Windows, NI Software	National Instruments		1	$649.75	$649.75
Shipping and Handling Fee	National Instruments		1	$39.68	$39.68
				Subtotal:	**$4,177.83**

Meters and Sensors

Part	*Vendor*	*Item #*	*Qty.*	*Price*	*Total*
Output Type 4 to 20mA current EC meter	Instrumart	GF 3-2850-52	6	$472.00	$2,832.00
Special Order conductivity probe 3-2841-1	Instrumart	GF 3-2841-1C	6	$419.00	$2,514.00
1.0" Doppler Transit Time Flow meter	Omega Systems	CSLFB10 H	10	$616	$6,160.00
1.5" Doppler Transit Time Flow meter	Omega Systems	CSLFB15 H	2	$722	$1,444.00
30PSIG stainless steel Transducer	Clark Solutions	100-30PSIG	12	$393.25	$4,719.00
30PSIG ceramic Transducer	Clark Solutions	511-30PSIG	11	$175.00	$1,925.00
Tank Level Meter	EchoSonic II	LU 27	4	$550.00	$2,200.00
				Subtotal:	**$21,794.00**

Wiring

Part	*Vendor*	*Item #*	*Qty.*	*Price*	*Total*
14" Cable Ties	Lowe's	76027	1	10.31	$10.31
18 gauge 3 conductor wire 50' bundle	Lowe's	356016	5	10.97	$54.85
PVC 1G Type FSS Box M	Lowe's	115867	5	4.67	$23.35
WaterProof Aqua Red 20PK	Lowe's	242242	1	8.94	$8.94
1 Gang Toggle Switch	Lowe's	254885	5	1.57	$7.85
18 gauge 3 conductor wire 50' bundle	Lowe's	356016	3	10.97	$32.91
Waterproof Aqua Orange 25	Lowe's	242257	5	9.27	$46.35
Waterproof Aqua Red 5PK	Lowe's	242239	2	2.79	$5.58
500' coil of 18 gauge 3 conductor wire	Home Depot	278319	1	69	$69.00
Blue Wing nut 10 BAG ID	Lowe's	46602	4	2.71	$10.84
Black Liquid Electrical Tape GB	Lowe's	118455	1	6.95	$6.95
Sensor Wiring	McMasterCarr	70985K82	6000	0.22	$1320.00

Variable Power Supply	Amazon	HY300D	1	110.85	$110.85
Cable Ties	Lowe's	292690	1	$15.97	$15.97
				Subtotal	**$2123.75**

Grand Total:	**$35,270.68**