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Nicaragua Water Distribution System

Leah Bensching
Santa Clara Univeristy

Jamie Monk
Santa Clara Univeristy

SANTA CLARA UNIVERSITY

Department of Civil Engineering

I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

Leah Bensching and Jamie Monk

ENTITLED

NICARAGUA WATER DISTRIBUTION DESIGN

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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Leah Bensching & Jamie Monk

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Abstract

In developing nations, such as Nicaragua, water security issues affect a large portion of the population. A lack of clean and secure water negatively causes many public health, environmental and economic concerns. This project addresses the need to develop a water distribution system to a rural community in Nicaragua. The proposed solutions will allow the community to choose more resilient design options to ensure reliable water delivery throughout the community.

By using NeatWork, a Nicaraguan based system, and WaterGEMS, which is more commonly used in the United States, it was determined that designing for 100% reliability was the most responsible approach, especially for community with growing populations. This would allow the community to receive ample water in more extreme circumstances, instead of merely average circumstances. The addition of a loop, or redundancy, would protect the integrity of the system by allowing water to be re-routed if a section of the system is compromised.

Introduction

In September of 2015, the United Nations presented the Sustainable Development Goals. Theses 16 goals work to “end poverty, protect the planet, and ensure prosperity for all,” and range from ending hunger to improving education for women (Sustainable). If the United Nations hopes to accomplish these goals by 2050, access to potable water is key. With this in mind, this project focuses on improving access to potable water for a rural community in Nicaragua by designing a water distribution system. The design primarily focuses on three of the Sustainable Development Goals: Clean Water and Sanitation, Industry Innovation and Infrastructure, and Climate Action.

According to the United Nations, 663 million people are still without a source of water and 1.8 billion people use a source of water that is contaminated. These statistics are the root of the goal for Clean Water and Sanitation. The most important aspect of this goal is "universal and equitable access to safe and affordable drinking water for all" (Sustainable). To work toward achieving this goal, this water distribution system design aims to provide a reliable source of water while minimizing effects on the surrounding ecosystem. It is not only important to design systems to meet the needs of people now, but to meet their needs for generations to come.

The United Nations believes that the connection between the goal of Industry, Innovation and Infrastructure and the overall economic success of a community are directly related. The goal focuses on improving existing infrastructure with new technologies and expanding it to communities that currently do not have reliable access. Strong local infrastructure is positively correlated to the success of a community by providing more reliable utilities and support to local businesses. Specifically, a water distribution system can improve the health of a community and limit time needed to collect water, allowing residents to have more time to work toward financial security and prosperity.

Climate Action is a two-part goal. It first focuses on minimal environmental impact while still working to achieve other Sustainable Development Goals. Second, Climate Actions identifies the importance of considering future climate change in the design of new infrastructure, so that communities are prepared for the changing climate patterns.

A core value of the Sustainable Development Goals is a call for action to address climate change while improving the lives of people around the world. From 1880 to 2012, the average global temperature has increased 0.85 degrees Celsius and the sea level rose 19 cm (Sustainable Development Goals). It is important for all engineers to keep in mind the effects of their designs on the environment. In many communities, infrastructure is not designed to withstand changing climate patterns. In the case of water, this means longer periods of drought and more intense floods, especially in Central America.

Project Background and Motivation

As outlined by the Sustainable Development Goals, water scarcity is an important issue that needs to be addressed around the world. There are two types of water scarcity: physical and economic. Physical water scarcity is when a region does not have enough water to available to supply the population. Economic water scarcity occurs when a region has enough water but does not have the infrastructure to deliver it to the people. Both of these are highlighted in various geographic regions in *Figure 1*. An example of a country with economic water scarcity is Nicaragua.

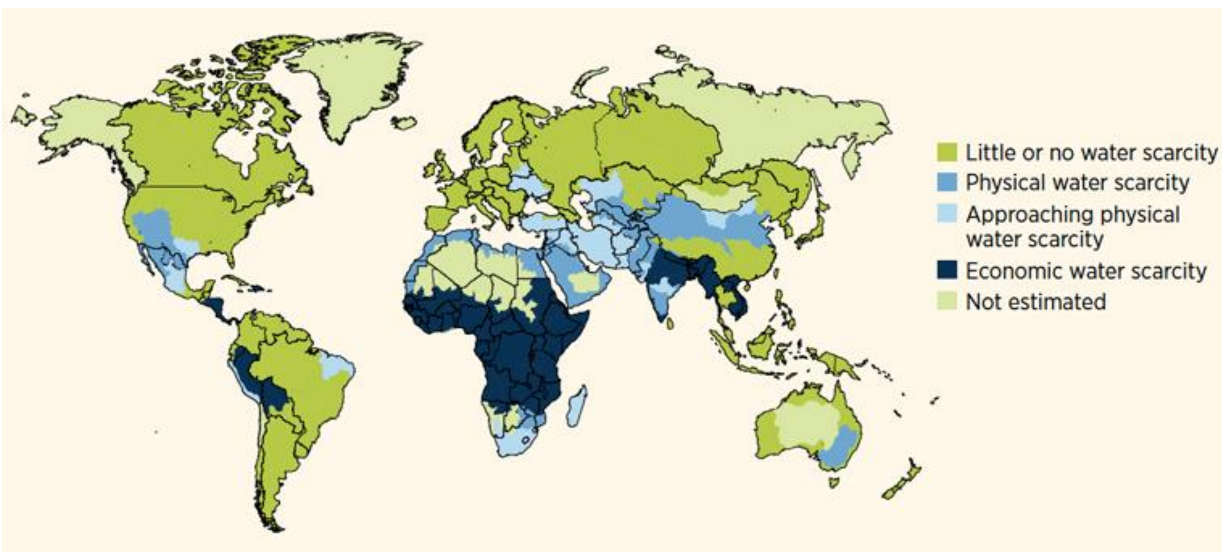

***Figure 1*: Global Water Scarcity from United Nations World Development Report 2012**

As in many Central American countries, Nicaragua is categorized as a tropical climate with a dry and wet season. During the rainy season, which takes place from June to December, the country receives approximately one meter of precipitation per year (Nicaragua - Climate). The regions along the Caribbean coast and the adjacent mountains receive more precipitation than the western half of the country, where the capital city of Managua, lies.

Although plenty of rainfall occurs within the country, Nicaragua is categorized as an economic water scarcity region because the majority of citizens lack access to potable water (United Nations). A variety of environmental, political and economic factors play into the water security issues that continue to inhibit the country from further development. In 1998, Hurricane Mitch caused intense mudslides and floods, resulting in thousands of deaths and about $1 Billion (USD) of damage to an already fragile infrastructure. The Nicaraguan Revolution caused extreme separation and distrust between the government and its people, resulting in a large division of resources. As the second poorest country in Latin America, it has a largely uneven distribution of wealth. This affects access to clean water for the rural, agricultural communities that produce 18% of the total GDP.. The large disparity between the service-based urban population and the farmers in the rural regions of the country have sparked an interest in the water security dispute (CIA World Factbook)

Currently, one third of the people living in rural communities in Nicaragua do not have access to clean drinking water. Nicaragua has many of sources of fresh water, but most of it is either not safe to drink or not accessible due to government disputes over water rights. Nicaragua is considered at “high risk” for disease, including bacterial diarrhea, hepatitis A and typhoid fever (CIA World Fact Book). This is mostly due to limited access of potable water throughout the country. In addition, in-person surveys show that 76% of residents have access to potable drinking water, but in the last five years the quality and quantity have decreased (Johnson). Local access to water includes nearby streams, wells, and springs, which are considered communal by Nicaraguan law; however, the private land surrounding the water sources often blocks the public from accessing these sources.

With the help of Dr. Chris Bacon, a professor of Environmental Studies and Sciences at Santa Clara University, a Nicaraguan based non-governmental organization (NGO) called ASDENIC (La Asociación de Desarrollo Social de Nicaragua) was collaborated with to address shortcomings in their current potable water supply distribution designs. ASDENIC focuses on community driven projects that use technology and engineering to address the needs of the people. They identified the demand for increased supply of potable water to El Bramadero, a rural community in the northwestern, mountainous region of the country. El Bramadero was chosen due to the increasing population in the region and existing system in need of repair. In addition, they provided valuable context regarding not only the geography of the land, but also the cultural climate of the region. Working with local NGOs, such as ASDENIC, is crucial to the success of projects in developing countries because it allows engineers the opportunity to better understand and address the needs of the people.

Project Objectives

The goal for this project was to design a more reliable and resilient water distribution system for a rural community in northwestern Nicaragua called El Bramadero. There are currently 800 residents in the community, but they expect significant growth over the next 20 years. The system is designed for 20% growth or 950 people. According to field information provided by ASDENIC, The existing system has 13 tap stands, but many of them are broken or are unused because of their location. The existing system must either be completely replaced or retrofitted to meet the growing demand.

The water distribution system will draw from a local source. Information from ASDENIC tells us that the source does not have a history of contamination and most households have personal water filtration units, so a treatment system does not need to be installed. There is a significant amount of sediment in the stream, so a sedimentation basin will be used at the source to remove it.

Considering the Sustainable Development Goals previously discussed, we identified three objectives to guide the design process for our project and future community projects:

1. Design a comprehensive system that delivers a dependable water supply to the community with minimal effects on the local ecosystem

In order to truly help the citizens of El Bramadero, the water distribution system needs to function at a high reliability factor. Certain design considerations must be made to make sure the system functions in average and worse case scenarios. This includes designing for the expansion of the community and making sure not to deplete necessary resources.

2. Compare and analyze designs from NeatWork and WaterGEMS

NeatWork is a Nicaraguan based software that specializes in gravity fed water designs and is available without cost. WaterGEMS is more commonly used in the United States because of its many design features and its high cost. The benefits and shortcomings of both platforms were analyzed in order to present ASDENIC to aid in interpreting results..

Ethical Analysis

There are many moral and cultural implications to consider during the design of a water distribution system. To ensure the highest ethical conduct throughout the project, good relations must be maintained with all involved parties. It was necessary to maintain open communication with the contacts at ASDENIC and in the community that relate the details of the project to the people of El Bramadero. The most ethical way to complete the design on the water distribution system was to consider the needs of the community during all phases, especially since the citizens will be completing all of the labor. Once completed, the design was presented with an honest recommendation for the improvement of the community's access to water.

The short-term effects of a new water distribution system are that there will be limited access to water during construction. While not ideal, it is necessary to remove the current system in order to allow for the new system to be installed properly. During this period, the community can retrieve water from the source directly and continue to use the household filtration unit in order to remove sediment, or water can be shipped in. The second option can be very expensive and is recommended for drinking water only. While this solution is temporary, it solves the main issue of water demand for El Bramadero during this transition.

The long-term implications of the project focus on the environmental implications and security risk. The Ministry of the Environment and Natural Resources will have jurisdiction over our project. ASDENIC also has environmental protocols for all of their projects. Unfortunately the most common building material for water distribution systems is PVC, which is known to be destructive to the environment. PVC has shown to contain toxins that, over time, affect the soil quality surrounding the pipe. Even though it is environmentally destructive, this material is the most sensible choice because of its availability in Nicaragua and general cost effectiveness. The lack of a more beneficial choice lead to the use of PVC in this distribution system. The best way to mitigate this risk is to use the highest-grade material and recommend annual testing of the soil conditions along the pipeline. There is also security risks in the project occur after completion. Vandalism is a reality for many projects in all locations. From the onset of the project, the community must show support and promise to protect it. Because of the political disputes around water rights in Nicaragua, it is impossible to guarantee the complete security of the system, but if the citizens of El Bramadero can agree to take care of the distribution system over the lifespan there is a greater chance for success.

Related Non-Technical Issues

When working with rural communities, there are many non-technical factors to consider in design. Most importantly, the cooperation of the community is key. It will primarily be the responsibility of the community to construct and maintain the water distribution system. If the community is not fully on board, the project will not be successful. The largest obstacle to understanding the community needs is the language barrier. We focused on using clear language throughout the project to avoid misunderstandings across translations. Software and funding need to supply clean water are often unavailable to Nicaraguans, which makes it difficult to continue to improve infrastructure. Working with ASDENIC allowed us insight into Nicaraguan culture and guidance for how to engage with the community.

Another important aspect when designing for the community is the financial commitment required by the project. Rural communities are often required to fund and develop their own innovations with the help of local engineers. The initial capital needed for the project can be extremely stressful on the local government and citizens, especially considering residential fights for water rights against agricultural and mining industries. The best way to manage the financial risk is to decrease the amount of maintenance costs for the community. This can be done by using responsible, sustainable, and locally sourced materials, including local PVC suppliers and and sustainable faucets.

As in many developing countries, the political climate plays a strong role in the distribution of resources. Water rights are a controversial issue in Nicaragua because of water's importance to the agricultural and industrial industries that make up the majority of their GDP. The tension around water rights began in 1979 with a political revolution and carried through until the turn of the century, opening up new channels for political involvement in national and local government, such as the Comités de Agua Potable y Saneamiento (CAPS). After Hurricane Mitch struck in 1998, Nicaragua received a $21 million dollar (US) loan to increase the amount of public-private partnerships in the water and sanitation sector. CAPS grew as a non-formalized community based water association to provide potable water access to over 1 million rural residents in the poorest parts of the country. Despite their ability to deliver this crucial service to areas that are not reached by state programs, they have no formal state recognition or legal priority (Romano). Due to the economic disparity, one third of the country still experiences limited access to clean drinking water. Even though the design does not address water rights, it is important to keep in mind for future applications of water distribution systems in Nicaragua.

Design Information

El Bramadero is a community of 175 families with a population of 800. Due to expected population growth, the system will be designed for 950 people. ASDENIC identified a source that can provide 1.14 liters per second, which is equivalent to 98 liters per person per day. This is well above the 15 liters per person per day recommended by the World Health Organization (World Heath Organization). The existing system has 13 access points (faucets). To have convenient access for all citizens of El Bramadero, old tap stands will be replaced and the number of tap stands will be increased to 16.

The source is in an ideal location because it is at a higher elevation than the community, allowing for the design of a gravity driven system. By not using a pump, the cost of the system decreases drastically. The existing path of the system was found to have the most workable topography. It avoided the steep slope in the valley while staying in proximity to the existing houses. The proposed path can be seen in *Figure 2*.

***Figure 2*: Aerial view of El Bramadero showing pipe routs**

The piping system is shown in three sections, the main branch (red), the north branch (orange) and the loop addition (yellow). The main branch and north branch make up the existing system. To identify the best option for El Bramadero, a cost analysis of three designs was done. In WaterGEMS, models were analyzed for the system with and without the loop addition. In NeatWork, only a model was analyzed for the system without loops due to constraints of the software.

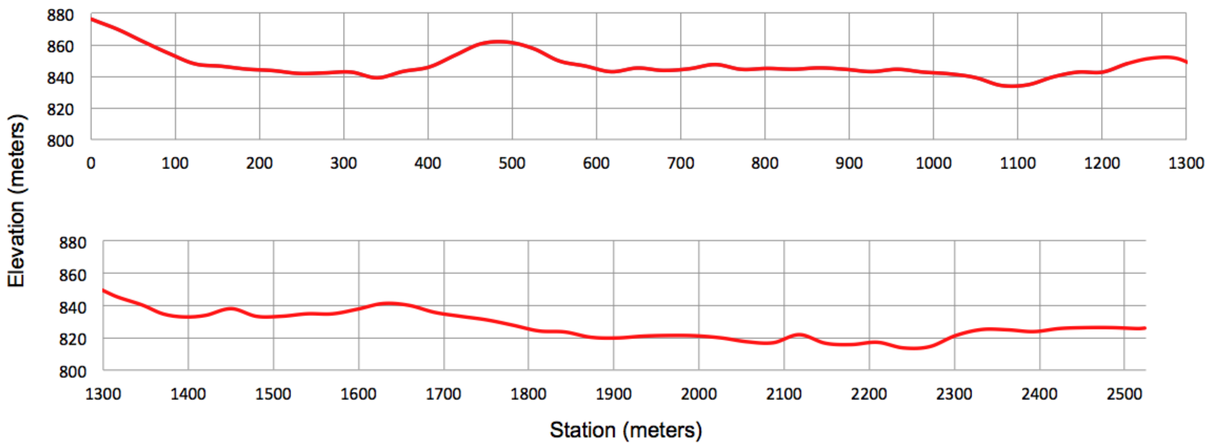

Figure 3: **Topography of Main branch showing a pressure head of 50 meters**

Figure 3 shows the topography of the main branch, which begins at an elevation of 875m and ending at an elevation of 825m. This provides 50m of pressure head, or 490 kPA of pressure, for the system. The topography also shows that there are many relatively high and low points throughout the system. At the high points, air-release valves will be installed to allow the removal of air pockets that are at risk of forming in those locations, and at the low points sedimentation release valves will be installed to allow sediment that has settled to be removed. It is also important to notice the relative low point of 840 m at station 350 and the hill between stations 400 and 600 that peaks at 860 m. The first community houses are located on the backside of the hill near station 550. The initial design placed a tank near those houses for easy access, but the final design moved the tank to the top of the hill to allow for more pressure throughout the system.

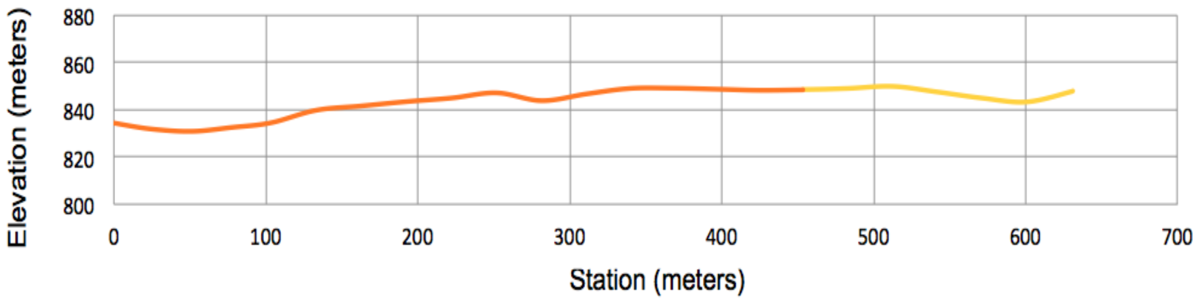

Figure 4: **Topography of the North Branch in orange and the Loop Addition in yellow.**

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of flow through the North Branch is dependent on whether or not the loop is present. Without the loop, the water flows uphill from station zero to station 450. As seen in *figure 4* without the loop**,** the water will flow uphill, left to right. With the loop addition, the water will flow the opposite direction from station 630 to zero where it will re-enter the main branch. The loop addition allowed the water to flow with decreasing elevation throughout the system, which will provide more uniform pressure distributions.

As requested by ASDENIC, the system will be modeled in two different software packages, NeatWork and WaterGEMS. NeatWork is Nicaraguan based software that designs specifically for gravity-fed water systems using the Darcy Weiss Bach friction equation. It is available free of charge on the Neatwork official site. It runs using a 2010 version of Java and is not compatible with any new versions. The system has a simple interface and allows for information to be copied in from other tools such as Excel. It works by defining the topography through the designation of the coordinates and elevation of the tank, each branch node, and any faucets in the system. From there, specifying a variety of conditions specific to the project creates a design. Once the system is designed, a variety of simulations can be run to predict how the system behaves in different situation. The simulations are run using the Monte Carlo

Method. The main drawbacks of the NeatWork software are its inability to allow redundancies and include more than one tank in the design.

WaterGEMS is more commonly used in the United States and requires that a license be purchased from Bentley Software. It uses the Hazen Williams friction equation and offers a wide variety of design options that allow the system to be customized. While the data entry method is more tedious than NeatWork since it is not compatible with Excel, its capabilities are give accurate results and allow for specific demand to be designed and analyzed. The capability of WaterGEMS taken advantage for this project is its ability to design with loops and redundancies. This will increase the reliability and resilience of the system. The Darwin Designer tool in WaterGEMS optimizes a system for cost, which allows for more economic designs and allows the designs to be compared to NeatWork.

The system will be designed with PVC because it is the most common material in the region. Its easy installation, strength and lightweight add to its versatility and practicality. PVC, however, is not environmentally friendly because it leaches chemicals into the soil. There is currently no reasonably priced alternative to PVC for small piping systems. Although ASDENIC did not provide any budget constraints, it is important for projects in developing communities consider the cost. NeatWork comes with a database of PVC pipes sizes and costs. To ensure the uniform comparison between all models, the information provided in NeatWork was also used in the WaterGEMS model.

The loop was placed near the center of the system because it is near the majority of the houses, the school and other community buildings. The taps at the community center will probably get the most use because of the dense population increasing the risk of misuse and breaks. By inserting the loop, it will protect the community against a system-wide failure and provide a more resilient and reliable source of water by allowing a shut off without loss of service. The analysis of both a loop and non-loop system was done and the cost was compared to ensure the loop addition is worth the investment, which is detailed in the *Design Alternatives Section*.

The demand at each of the 16 tap stands will be a minimum of 100 ml per second, but we will aim to provide at least 200 ml per second to most tap stands. 200ml per second is the recommended value in NeatWork, so will be used for consistency across all three models. The minimum pressure in the tap stands will be 5kPa to ensure enough pressure to deliver a usable amount of water. The maximum pressure in the system will be 175 kPa to ensure the PVC does not burst. The velocity throughout the whole system will aim to be between 0.5 meters per second and 3 meters per second. These values are recommended by "Field Guide to Environmental Engineering for Development Workers" (Mihelcic). The lower limit is set to prevent sediment from settling and clogging the pipes, and upper limit is set to prevent turbulence from adding air pockets to the system.

Design Standards

The basis for design will come from the ASCE specification for a gravity fed water systems, specifically referencing "Field Guide to Environmental Engineering for Development Workers" (Mihelcic). The hydraulic equations are the same for any piping system, but there are multiple ways to calculate the friction loss from the pipes. The most common are the Darcy-Weisbach and the Hazen- Williams equations.

The governing equation for a hydraulic system comes from the principle of conservation of energy. The energy equation for hydraulic systems is

$$\frac{P_1}{\gamma} + \frac{8Q_1^2}{g\pi^2 D_1^4} + Z_1 + H_p = \frac{P_1}{\gamma} + \frac{8Q_2^2}{g\pi^2 D_2^4} + Z_2 + \sum H_L. \qquad (1)$$

Equation 1 is used in both NeatWork and WaterGEMS. In the first term, P is the pressure, γ is the specific weight of water (62.4. lb/ft^3). The second term includes the flow rate Q (ft^3/s), gravity g (32.2ft/s^2) and the diameter D in feet. Z is the change in elevation from a reference point in feet, H_p is the pressure head supplied in feet by the pump and h_L is the head loss from friction and minor losses.

Equation 2 is used to find the pressure head loss (h_L) in meters for the Darcy Weisbach Method.

$$h_L = 16f\,\frac{LQ^2}{2g\pi^2D^5} \qquad (2)$$

The friction factor is found from the Moody Diagram shown in *figure 5* by using the Reynolds Number and pipe roughness, the NeatWork program uses this method.

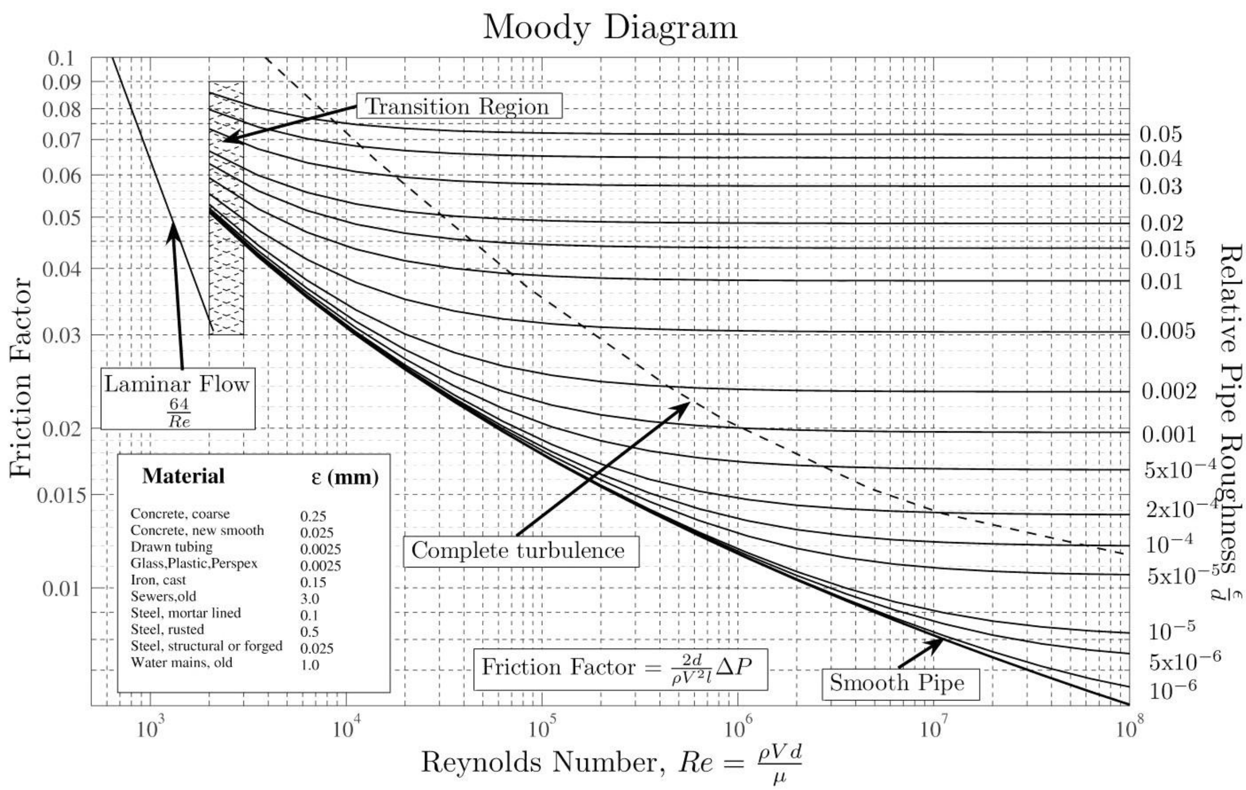

Figure 5: Moody Diagram for Darcy Weisbach Frication Factor

The pipe roughness (ε), for PVC as defined by NeatWork is 0.0015. And the equation for the Reynolds Number is

$$Re = \frac{\rho V d}{\mu}. \tag{3}$$

Where ρ is the density of the liquid (1,000 kg/m^3 for water) V is the velocity in meters per second, d is the diameter in meters and μ is the fluid viscosity (1.002 x10^{-4} Pa-s at 20 degrees C).

The second method is the Hazen William Equation, which uses a coefficient C to account for material roughness. The equation for head loss using with the Hazen Williams Equation is

$$h_L = \frac{10.67 Q^{1.85}}{C^{1.85} d^{4.865}} \tag{4}$$

The C coefficient for PVC is 150, Q is the flow in m^3 per second and d is the diameter in meters. The Hazen William method is the default in WaterGEMS.

Design Alternatives

The initial design idea focuses on establishing a system that would operate efficiently with the given restrictions. ASDENIC proposed an initial route for the Main Branch and North Branch of the Pipe, as seen in *figure 6*.

Figure 6: **Areal view of the system with tap stands and take locations show**

It was confirmed that the route avoided existing structures and steep elevation changes so it was deemed acceptable for all three designs. The initial design called for a sedimentation tank and storage tank at the source, as well as a storage tank at 648 meters in order to allow the community convenient access.

First, the design proposed by ASDENIC without the loop was run in NeatWork with a resilience factor of 0.75 and the other design parameters outlined in the Design Information section. The resilience factor determines the fraction of scenarios in which the system will meet the demand of the community. The initially recommended system reported a total cost of $25,773.74 (USD), which was deemed too expensive for a community of this size. Upon closer examination, it was found that the pipe diameter leading into the second tank was ½” and the exiting recommended pipe size was 8”. It is unreasonable to switch from a ½” pipe to an 8” pipe, so the design need to be rethought. Larger pipe sides like 8” and 6” pipe were also driving up the cost of the system. The design without the loop was then tested in WaterGEMS, but a system failure occurred. The Darwin Designer with in WaterGEMS would not recommend large pipe sizes to overcome limited pressure head. Large pipe sizes decrease the velocity thus decreasing the friction loss in the system. This confirmed the need to move the location of the tank.

The tank was moved to station 493 with an elevation of 861m providing 40 m of pressure head or 392 kPa of pressure for the system. The new location for the tank is before the first tap stand allowing the storage tank at the source to be removed, cutting out that additional cost. The water would now flow through the sedimentation basin at the source and then through 490 meters of pipe into the storage tank. From there, the water would be delivered to the rest of the community. The three alternatives were then run for this new tank location.

NeatWork Design

The NeatWork design resulted in the cheapest cost for the piping system at $4,766.22. But upon closer examination, the software is set to design for less than 100% reliability, making it more likely to optimize cost over efficiency. While this delivers water to El Bramadero for the majority of the time, the goal of this project was to increase the conditions to 100% reliable.

WaterGEMS Design without Loop

The total cost piping for the WaterGEMS model without the loop came to $5,528.78. Nearly $2,000 of that was spent on a total of 801 meters of 1 ½” pipe. This was also the most length of once size of pipe. The next largest cost was $1,040 for 441 meters of 1 ¼” pipe. There is 113 meters of 1” pipe with at total cost of $877, 661 meters of ¾” pipe for $951 and 982 meters of ½” pipe for a total cost of $686.

WaterGEMS Design with Loop

The pipes for the WaterGEMS design with the loop came to a total cost of $5,170. The majority of the cost came from the 1286 meters of ¾” pipe with a total cost of $1,851.48. This is a much smaller pipe size compared to the majority of the cost of the *WaterGEMS design without the Loop* which came from 1 ½” pipes. 1 ½” pipes for this model were the second most total cost at 497 meters for $1,217. There was significantly more ½” pipe in the system than other design alternatives with 928 meters for a total of $974. There were 388 meters of 1 ¼” pipe and 113 meters of 1” pipe at $915 and $211 total respectively.

To see the engineering effects of the difference between the WaterGEMS design with and without a loop, the Hydraulic Grade Line is compared to the elevation across the main branch of the system. Both designs have a pressure head higher than the elevation, which implies positive pressure throughout the system. The WaterGEMS design with the loop, highlighted in yellow, slopes at a more gradual rate. The loop gives higher-pressure heads at the farthest faucets in the system, which is to the benefit of the Community.

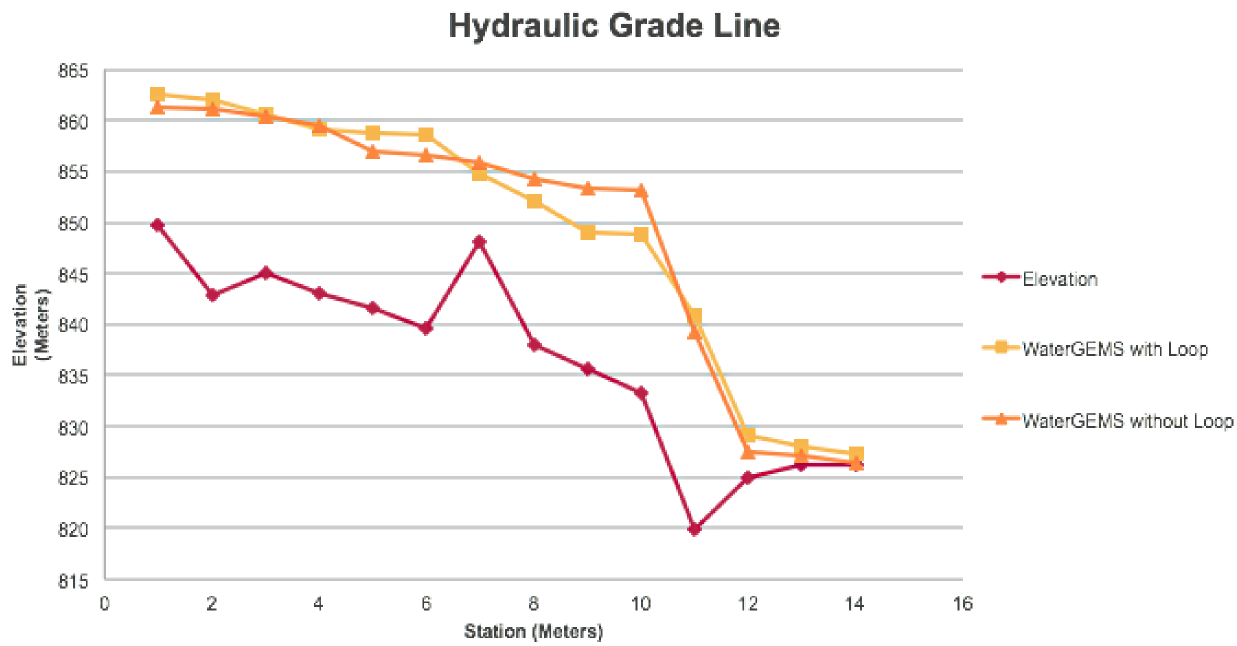

Figure 7: Hydraulic Grade Line for WaterGEMS Modles with and without Loop

Cost Comparison of Design Alternatives

The real difference in the various designs can be seen in the cost differentiation. During the initial design phase, it was discovered that the NeatWork program included a pipe information database that contained useful information such as the size of piping available and the unit cost, as seen in *Table 1*. This database was used in all three designs in order to ensure a universal comparison was made.

Table 1: **Unit Cost of Pipe Sizes ranging from 1/2" to 2" in U.S. Dollars from NeatWork**

Nominal Pipe Diameter	U.S. Dollar per Meter
1/2"	1.05
3/4"	1.44
1 "	1.87
1 1/4"	2.36
1 1/2"	2.45
2 "	3.68

Each model provided the total length of each pipe size selected. By using *Table 1*, it was possible to determine the total cost for each pipe size in each system. NeatWork optimized not to use any of the 1 ¼" pipe size. The WaterGEMS model without the loop used the most of the 1 ½" pipe, which was the largest pipe selected by all three designs. The WaterGEMS system with the suggested loop in place cuts the cost of the amount of 1 ½" pipe used because the water is diverted in more directions, allowing more ¾" pipe to be used.

***Table 2*: Length and Total Cost Per Pipe Size in U.S. Dollars for Each Design**

	NeatWork		**WaterGEMS without Loop**		**WaterGEMS with Loop**	
	Length (m)	Cost (USD)	Length (m)	Cost (USD)	Length (m)	Cost (USD)
1 1/2"	647.256	$1,585.78	801	$1,962.45	497	$1,217.65
1 1/4"	-	-	441	$1,040.76	388	915.68
1"	1091.849	$2,041.76	469	$877.03	113	$211.31
3/4"	646.296	$930.67	661	$951.84	1286	$1,851.84
1/2"	198.115	$208.02	654	$686.70	928	$974.40

Table 2 shows that NeatWork provided the cheapest solution, and that lest cost effective design is the WaterGEMS model without a loop. The WaterGEMS alternative without the loop the the median cost.

Table 3: Total Pipe Cost Comparison in U.S. Dollars

NeatWork	**WaterGEMS without Loop**	**WaterGEMS with Loop**
$4,766.22	$5,518.78	$5,170.88

Supplemental Materials

In addition to PVC pipe, other materials must be considered in the overall cost of the system. Since the proposed location and number of tap stands is the same for each design, this information is considered supplemental. When exploring the design of the tap stands, concrete was deemed the best option because of its durability in extreme weather and stand up to to livestock. It is also an accessible material in Nicaragua. The materials needed for each tap stand include the faucet, concrete mix, rebar, galvanized pipe and PVC pipe. ***Table X*** shows the estimated cost (USD) for all 16 tap stands. Figure XXXX shows the sketch of a typical concrete tap stand for a rural developing community.

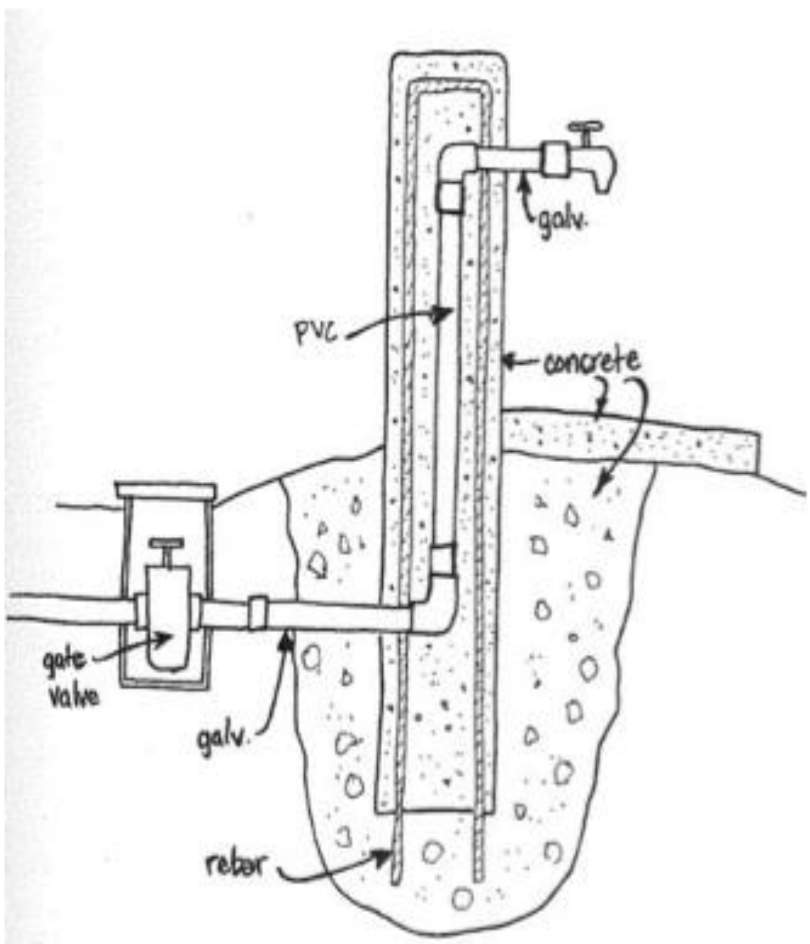

Figure 8: **Concrete Tap Stand Design (Mihelcic)**

Table 4: **Supplemental Material Cost**

Galvanized Iron Pipe	$27.09
PVC within Tap stand	$33.60
#4 Rebar	$299.52
Concrete	$255.68
90 Degree Elbow	$41.60
Faucet Heads	$117.60
Tank	$700.00
Sedimentation	$500.00
Sedimentation Valves	$555.00
Aeration Valves	$201.75
Total Supplemental Cost	**$2,731.84**

In addition to the tap stands, the sedimentation basin and storage tank were designed for the 1.15 L/s of flow from the source. The water first flows through the sedimentation basin to remove the majority of the sediment. The tanks were designed based on recommendations from *Field Guide to Environmental Engineering for Development Workers* (Mihelcic). The sedimentation basin needs to be at least 4 meters long. Most basins have a length to width ration of 1 to 4, so the basin will be 1 meter wide. A sedimentation basin does not store the water, water flows through it dropping the sediment. The final dimension for the tank should be 4 meters by 1 meter by ¾ meter. A storage tank needs to hold enough water for 1 hour of peak usage. For El

Bramadero, this is 4 square meters. The dimensions of the storage tank are not as important as the size. Any shape deemed most economic by ASDENIC will be acceptable.

Design Recommendation

When giving a final recommendation for the community of El Bramadero, it was important to look back at the Sustainable Development Goals: Clean Water and Sanitation, Industry Innovation and Infrastructure, and Climate Action. Clean Water and Sanitation emphasizes the importance of providing a reliable source of water to all, so it was decided to choose the most reliable system but still consider cost. The most reliable option is the WaterGEMS design with the loop because it provides an important resilience factor for the system. The loop is placed in the most population concentrated area of the community, so if a portion were to break, the people would still have access to water via the alternate pipe rout. Loops are not often used in developing communities because it adds cost, so using the loop, aligns with the goal Industry, Innovation and Infrastructure. In the case of El Bramadero, the pipe cost for the looped system is less expensive than the non-looped system. However, it is important to keep in mind that the addition 80 meters of pipe will cost the community labor time.

The total cost of the looped system will be $7,902.72 (US). Although the NeatWork design was the least expensive, the program designs for 75% reliability. Due the increasing population, it is important for the system to be extremely reliable. Ensuring a reliable source of water for the growing population is the final reason to recommend the slightly more expensive looped design from WaterGEMS.

Future Research

The analysis of the looped and non-looped water distribution system in WaterGEMs showed that in the case of El Bramadero, a looped system can be less expensive. Although there is more total length of pipe, the lower cost is due to smaller pipe sizes that are used in the loop when the water is diverted to two pipes. To expand our knowledge of piping systems in rural areas, it would be beneficial to do a cost- benefit analysis of loop additions in a variety of communities. Factors such as population size, topography, available pressure head and source flow vary for every community. Analyzing each in a variety of communities will give engineers a better sense of when a loop addition will be more cost effective or overall cost less than a system without loops.

More specific to the community of El Bramadero, the location of tap stands and tanks can have significant influence on the system. Before a final design is decided, the tank location and tap stand locations should be analyzed further. The storage tank could be tested at different elevations on the hill at station 500. In addition, it could be moved to the source to see if the few meters of addition presser head are beneficial to the system despite not being in a convenient location for the community to monitor. Different configurations for the tap stands could also be tested. There are an infinite number of possibilities for tap stand arrangements, but by changing the locations of a few, a better understanding of the weaknesses in the system could be found.

Conclusion

The design methods presented all deliver a dependable water supply to the community of El Bramadero, while optimizing cost to ensure it will not cripple the people’s resources. This system is designed for the growth of the community over the lifetime of the system, allowing the people to reap the economic and health benefits of an in ground water distribution system. While this design is specific to El Bramadero, the key points of 100% reliability and material needs can be applied to other economically scarce water communities throughout the world.

Resources

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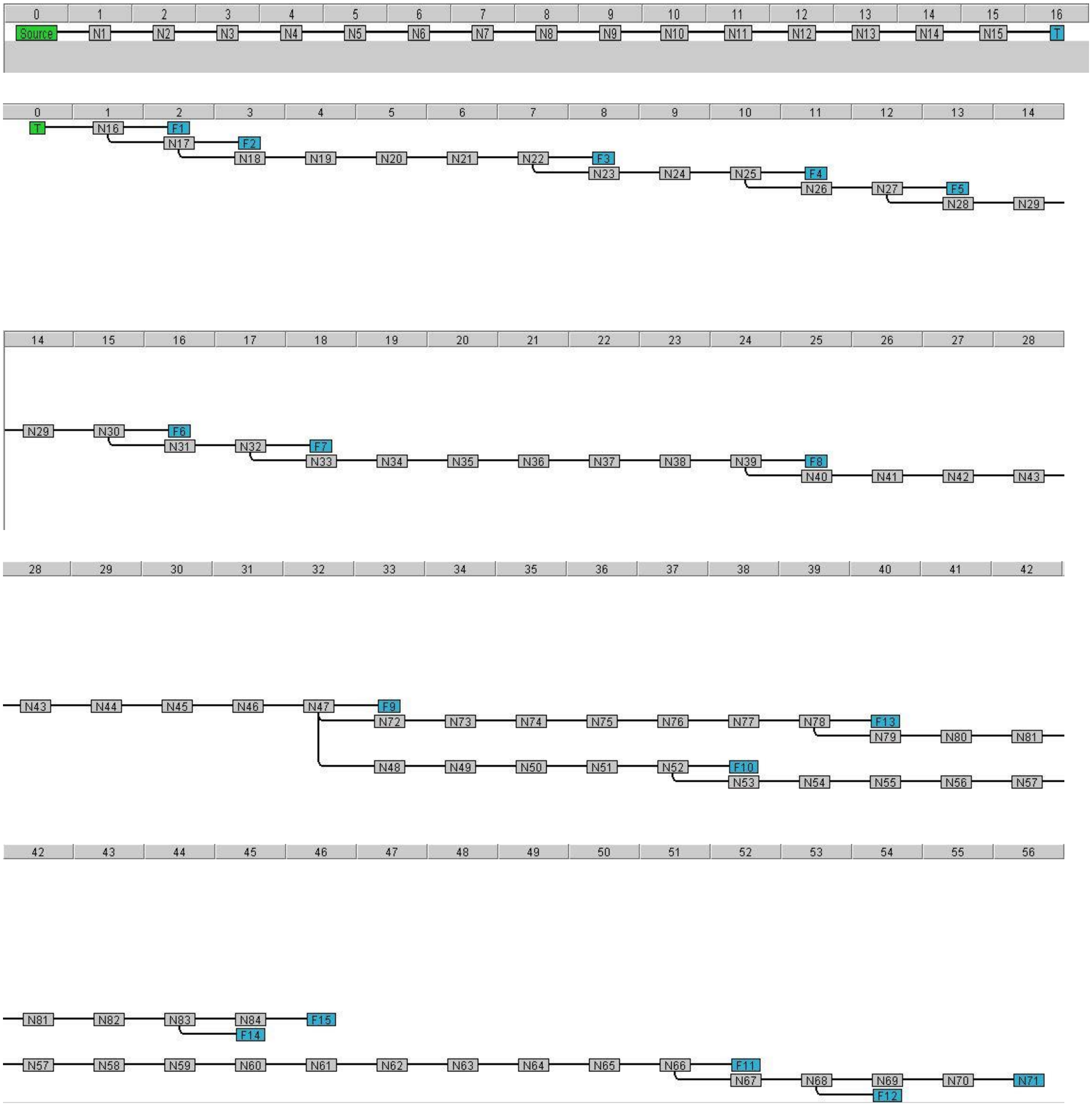
Appendix A

NeatWork: Tree View



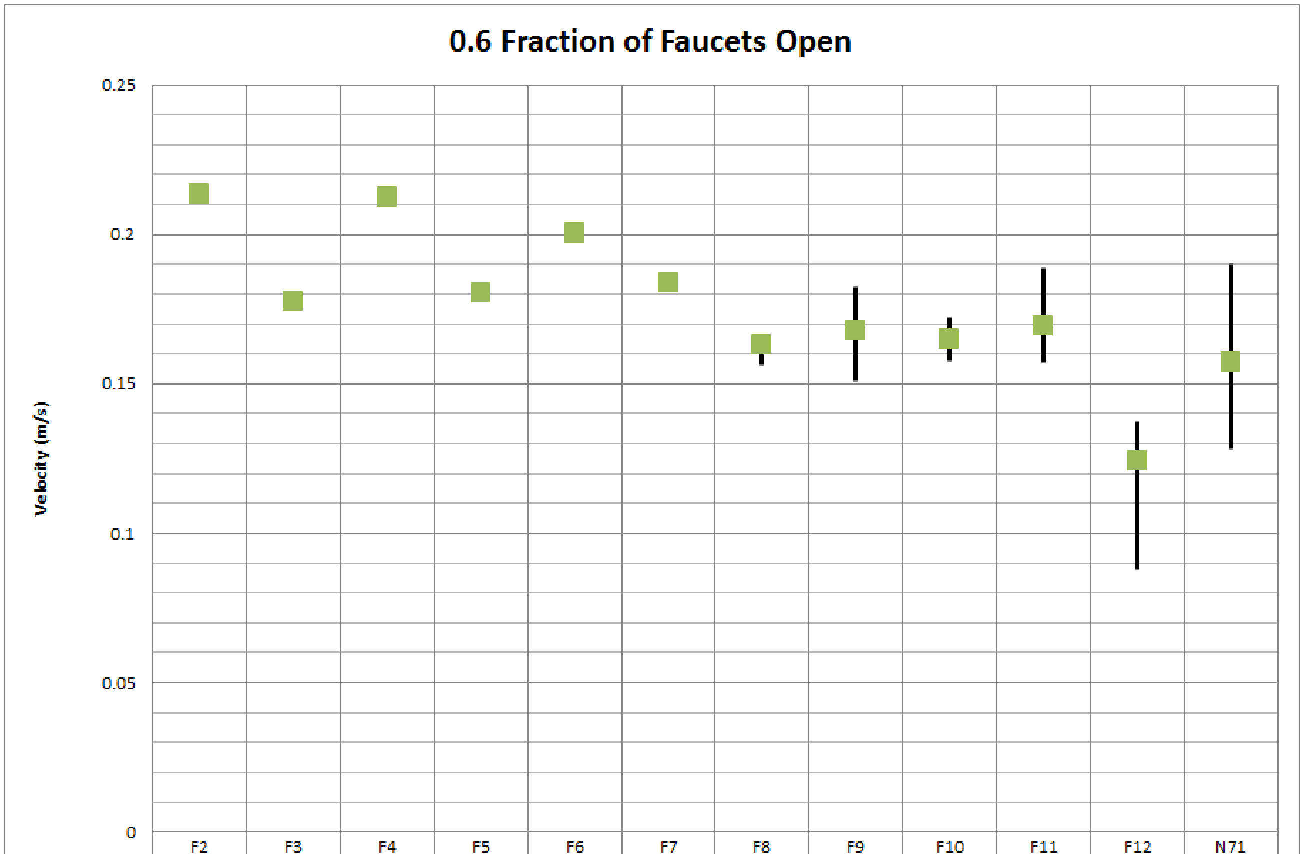
Appendix B: NeatWork: Solution

Begin	End	Total Length	Length 1	Diameter 1	Length 2	Diameter 2
Source	N1	30.866	24.000	0.2350	6.866	0.0182
N1	N2	30.866	24.000	0.2350	6.866	0.0182
N2	N3	30.866	24.000	0.2350	6.866	0.0182
N3	N4	30.866	24.000	0.2350	6.866	0.0182
N4	N5	30.866	24.000	0.2350	6.866	0.0182
N5	N6	30.866	24.000	0.2350	6.865	0.0182
N6	N7	30.866	24.000	0.2350	6.865	0.0182
N7	N8	30.866	24.000	0.2350	6.865	0.0182
N8	N9	30.866	24.000	0.2350	6.865	0.0182
N9	N10	30.866	24.000	0.2350	6.865	0.0182
N10	N11	30.865	24.000	0.2350	6.865	0.0182
N11	N12	30.865	24.000	0.2350	6.865	0.0182
N12	N13	30.865	24.000	0.2350	6.865	0.0182
N13	N14	30.865	24.000	0.2350	6.865	0.0182
N14	N15	30.865	12.865	0.2350	18.000	0.0182
N15	T	30.865	6.865	0.2350	24.000	0.0182
T	N16	30.865	30.865	0.0459	0.000	0.0000
N16	N17	61.730	61.730	0.0459	0.000	0.0000
N17	N18	61.730	61.730	0.0459	0.000	0.0000
N18	N19	30.865	30.865	0.0459	0.000	0.0000
N19	N20	30.865	30.865	0.0459	0.000	0.0000
N20	N21	30.865	30.865	0.0459	0.000	0.0000
N21	N22	30.865	30.865	0.0459	0.000	0.0000
N22	N23	61.730	61.730	0.0459	0.000	0.0000
N23	N24	30.865	30.865	0.0459	0.000	0.0000
N24	N25	30.865	30.865	0.0459	0.000	0.0000
N25	N26	61.730	61.730	0.0459	0.000	0.0000
N26	N27	30.865	30.865	0.0459	0.000	0.0000
N27	N28	61.729	61.729	0.0459	0.000	0.0000
N28	N29	30.865	30.865	0.0459	0.000	0.0000
N29	N30	30.865	30.865	0.0459	0.000	0.0000
N30	N31	59.957	59.957	0.0459	0.000	0.0000

N31	N32	29.092	29.092	0.0459	0.000	0.0000
N32	N33	58.184	58.184	0.0459	0.000	0.0000
N33	N34	29.091	29.091	0.0459	0.000	0.0000
N34	N35	29.092	29.092	0.0459	0.000	0.0000
N35	N36	29.092	29.092	0.0459	0.000	0.0000
N36	N37	24.946	24.946	0.0459	0.000	0.0000
N37	N38	24.945	24.945	0.0459	0.000	0.0000
N38	N39	24.945	24.945	0.0459	0.000	0.0000
N39	N40	59.583	59.583	0.0459	0.000	0.0000
N40	N41	29.791	29.791	0.0459	0.000	0.0000
N41	N42	29.792	29.792	0.0459	0.000	0.0000
N42	N43	29.791	29.791	0.0459	0.000	0.0000
N43	N44	29.792	29.792	0.0459	0.000	0.0000
N44	N45	29.791	29.791	0.0459	0.000	0.0000
N45	N46	29.791	29.791	0.0459	0.000	0.0000
N46	N47	30.590	30.590	0.0459	0.000	0.0000
N47	N48	53.594	53.594	0.0235	0.000	0.0000
N48	N49	30.590	30.590	0.0235	0.000	0.0000
N49	N50	30.590	30.590	0.0235	0.000	0.0000
N50	N51	30.590	30.590	0.0235	0.000	0.0000
N51	N52	30.590	30.590	0.0235	0.000	0.0000
N52	N53	61.181	61.181	0.0235	0.000	0.0000
N53	N54	30.590	30.590	0.0235	0.000	0.0000
N54	N55	30.590	30.590	0.0235	0.000	0.0000
N55	N56	30.590	30.590	0.0235	0.000	0.0000
N56	N57	30.590	30.590	0.0235	0.000	0.0000
N57	N58	30.590	30.590	0.0235	0.000	0.0000
N58	N59	30.590	30.590	0.0235	0.000	0.0000
N59	N60	30.590	30.590	0.0235	0.000	0.0000
N60	N61	30.590	30.590	0.0235	0.000	0.0000
N61	N62	30.590	30.590	0.0235	0.000	0.0000
N62	N63	30.590	30.590	0.0235	0.000	0.0000
N63	N64	30.590	30.590	0.0235	0.000	0.0000
N64	N65	30.590	30.590	0.0235	0.000	0.0000

N65	N66	30.590	30.590	0.0235	0.000	0.0000
N66	N67	61.180	36.000	0.0235	25.180	0.0182
N67	N68	30.542	18.000	0.0235	12.542	0.0182
N68	N69	61.084	61.084	0.0182	0.000	0.0000
N69	N70	30.542	30.542	0.0182	0.000	0.0000
N47	N72	7.587	7.587	0.0235	0.000	0.0000
N72	N73	25.540	25.540	0.0235	0.000	0.0000
N73	N74	25.540	25.540	0.0235	0.000	0.0000
N74	N75	25.540	25.540	0.0235	0.000	0.0000
N75	N76	25.540	25.540	0.0235	0.000	0.0000
N76	N77	29.833	29.833	0.0235	0.000	0.0000
N77	N78	29.833	29.833	0.0235	0.000	0.0000
N78	N79	59.667	59.667	0.0235	0.000	0.0000
N79	N80	29.833	29.833	0.0235	0.000	0.0000
N80	N81	29.833	29.833	0.0235	0.000	0.0000
N81	N82	29.833	29.833	0.0235	0.000	0.0000
N82	N83	28.676	28.676	0.0235	0.000	0.0000
N83	N84	57.352	30.000	0.0235	27.352	0.0182
N16	F1	5.000	5.000	0.0182	0.000	0.0000
N17	F2	5.000	5.000	0.0182	0.000	0.0000
N22	F3	5.000	5.000	0.0182	0.000	0.0000
N25	F4	5.000	5.000	0.0182	0.000	0.0000
N27	F5	5.000	5.000	0.0182	0.000	0.0000
N30	F6	5.000	5.000	0.0182	0.000	0.0000
N32	F7	5.000	5.000	0.0182	0.000	0.0000
N39	F8	5.000	5.000	0.0182	0.000	0.0000
N47	F9	5.000	5.000	0.0182	0.000	0.0000
N52	F10	5.000	5.000	0.0182	0.000	0.0000
N66	F11	5.000	5.000	0.0182	0.000	0.0000
N68	F12	5.000	5.000	0.0182	0.000	0.0000
N70	N71	8.367	8.367	0.0182	0.000	0.0000
N78	F13	5.000	5.000	0.0182	0.000	0.0000
N83	F14	5.000	5.000	0.0182	0.000	0.0000
N84	F15	33.676	18.000	0.0235	15.676	0.0182

Appendix C: Neatwork: Velocity at Faucet Heads



	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	N71
High (75)	0.2135	0.1776	0.2123	0.1806	0.2004	0.1838	0.1657	0.1824	0.172	0.1885	0.1371	0.19
Low (25)	0.2135	0.1775	0.2123	0.1806	0.2004	0.1836	0.1563	0.1507	0.1578	0.1572	0.0877	0.1279
Closing (50)	0.2135	0.1776	0.2123	0.1806	0.2004	0.1837	0.163	0.168	0.1651	0.1693	0.1244	0.1574

Figure C: Velocity at Faucets when 60% open given 100 simulations.

Table C: Velocity at Faucet Heads in m/s for 60% of Faucets Open

Faucet ID	Number occurrences	Min	< 10%	< 25%	< 50%	< 75%	< 90%	Max
F1	64	0.2124	0.2127	0.213	0.2138	0.2142	0.2145	0.215
F2	61	0.1788	0.1793	0.1797	0.1804	0.1812	0.1816	0.1826
F3	66	0.2161	0.2201	0.2218	0.2241	0.2262	0.2302	0.2325
F4	68	0.1506	0.155	0.1572	0.1593	0.1614	0.1637	0.1692
F5	55	0.1534	0.1575	0.1598	0.163	0.1648	0.1663	0.1705
F6	55	0.1589	0.1629	0.1664	0.1682	0.1704	0.1716	0.1767
F7	68	0.1294	0.1444	0.158	0.1621	0.1712	0.183	0.1935
F8	64	0.1478	0.1518	0.1567	0.1647	0.1803	0.1938	0.2214
F9	57	0.1152	0.1226	0.1356	0.1509	0.1705	0.1808	0.24
F10	58	0.1599	0.164	0.1688	0.1733	0.179	0.1876	0.2299
F11	49	0.1358	0.1493	0.1567	0.169	0.1878	0.2165	0.2622
F12	69	0.0609	0.0809	0.113	0.1297	0.1519	0.1961	0.2713
N71	66	0.0969	0.1198	0.1436	0.1684	0.1935	0.2767	0.3183

Appendix D

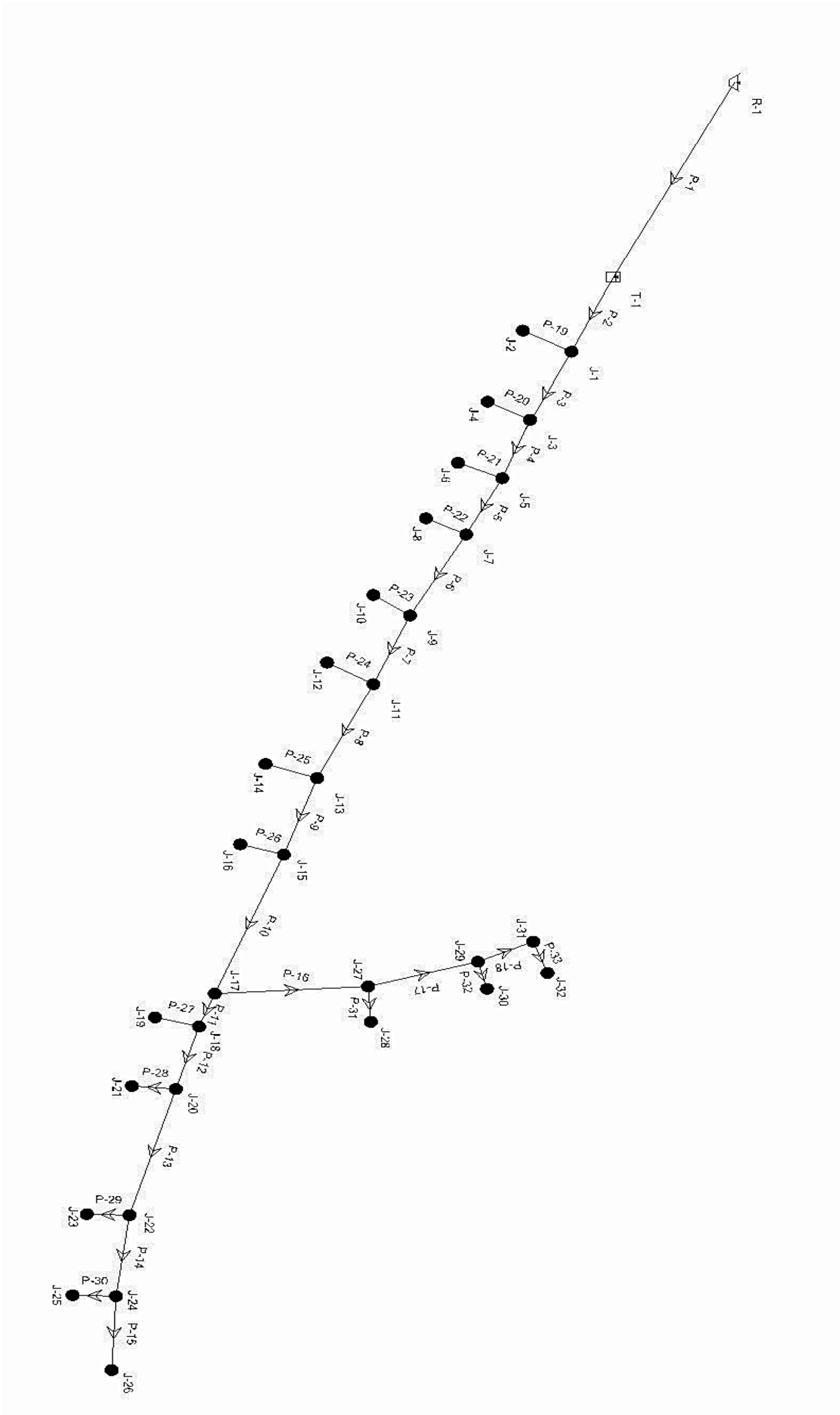
NeatWork: Node Pressures in Meters

Node ID	Minimum	Average	Maximum
T	0	0	0
N16	13.21	13.48	13.71
N17	29.95	30.65	31.42
N18	25.85	26.89	27.98
N19	26.5	27.71	28.95
N20	24.55	25.94	27.34
N21	20.97	22.52	24.08
N22	23.15	24.87	26.59
N23	21.67	23.61	25.43
N24	20.11	22.15	24.15
N25	20.29	22.44	24.65
N26	19.17	21.4	23.86
N27	20.4	22.67	25.26
N28	22.9	25.28	28.22
N29	27.41	29.85	32.97
N30	26.51	29.01	32.3
N31	17.69	20.2	23.69
N32	17.36	19.88	23.46
N33	7.97	10.45	14.28
N34	7.72	10.18	14.14
N35	13.61	16.14	20.22
N36	18.24	20.84	25.03
N37	23.51	26.17	30.47
N38	25.04	27.76	32.2
N39	23.72	26.5	31.09
N40	23.84	26.68	31.5
N41	23.53	26.4	31.34
N42	21.74	24.64	29.7
N43	21.49	24.42	29.6
N44	18.31	21.27	26.56

N45	14.6	17.59	23
N46	15.44	18.46	23.99
N47	19.56	22.62	28.26
N48	20.82	24.01	29.66
N49	21.89	25.43	31.42
N50	23.25	27.13	33.46
N51	21.71	25.93	32.6
N52	22.78	27.34	34.95
N53	20.28	25.29	55.17
N54	18.94	23.97	54.75
N55	18.21	23.25	54.93
N56	18.61	23.67	56.25
N57	20.1	25.18	58.65
N58	19.78	24.88	59.26
N59	13.86	18.98	54.25
N60	18.24	23.38	59.55
N61	18.16	23.32	60.39
N62	15.82	21	58.97
N63	18.39	23.59	62.45
N64	16.73	21.95	61.71
N65	8.95	14.19	54.85
N66	4.27	9.53	51.09
N66*N67	4.64	12.25	51.84
N67	4.24	11.53	52.37
N67*N68	2.93	10.14	51.24
N68	1.68	8.74	50.46
N69	0.47	17.63	49.89
N70	0.75	17.7	50.49
N72	20.99	24.5	42.08
N73	22.73	26.22	44.45
N74	22.81	26.27	45.16
N75	20.62	24.06	43.61
N76	17.78	21.32	41.53
N77	11.63	15.31	36.29

N78	8.96	12.77	34.52
N79	5.16	10.96	31.14
N80	3.02	8.72	29.21
N81	6.09	11.68	32.49
N82	2.88	8.37	29.49
N83	0.16	5.55	26.98
N84	0.39	10.04	27.6
N83*N84	0.39	10.23	27.3
N84*F15	0.45	10.06	27.71
F1	0	6.47	18.49
F10	0	18.02	56.3
F11	0	18.45	51.25
F12	0	15.97	49.9
F13	0	12.77	32.75
F14	0	11.96	27.19
F15	0	9.18	27.81
F2	0	12.43	29.6
F3	0	10.27	31.13
F4	0	14.26	33.15
F5	0	15.56	34.57
F6	0	15.31	36.46
F7	0	10.4	28.11
F8	0	14.12	38.17
F9	0	15.88	42.91
N71	0	16.56	50.2

Appendix E: WaterGEMS without Loop: Tree View



Appendix F: WaterGEMS without Loop: Solution

Table F1: Pressures in KPa at each junction as modeled in WaterGEMS

Junction	Pressure (Kpa)	Junction	Pressure (Kpa)
J-1	113.4	J-17	173.2
J-2	113.5	J-18	194.9
J-3	177.9	J-19	194.9
J-4	177.9	J-20	189.8
J-5	151.1	J-21	189.8
J-6	151.1	J-22	25.4
J-7	161.5	J-23	25.4
J-8	161.5	J-24	9.1
J-9	151.5	J-25	8.5
J-10	151.5	J-26	1.2
J-11	165.6	J-27	95.8
J-12	165.6	J-28	95.6
J-13	77.3	J-29	20.5
J-14	77.3	J-30	20.5
J-15	159	J-31	20.1
J-16	159	J-32	19.5

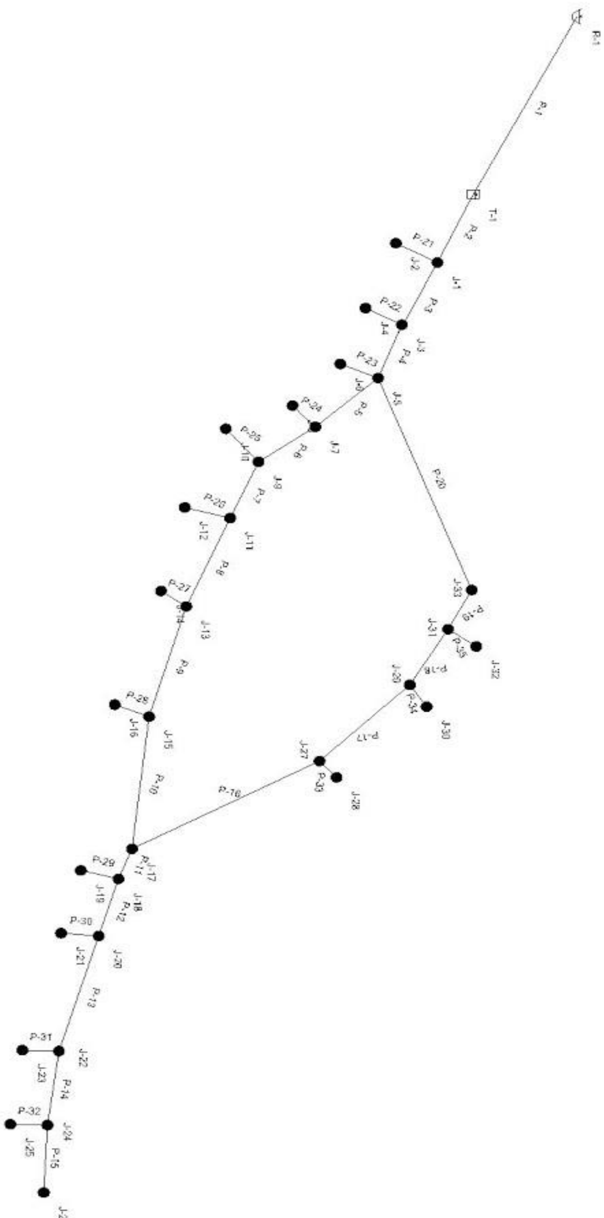
Table F2: Diameter, Cost, length and velocity for each section of pipe.

Pipe	Diameter (mm)	Diameter (in)	Cost per Section	Length (m)	Velocity (m/s)
P-1	18.2	0.5	517.6	493	0.6
P-2	30.4	1	117	63	0.83
P-3	45.9	1.5	151.2	62	0.36
P-4	45.9	1.5	453.7	5	0.36
P-5	39.1	1.25	291.4	185	0.5
P-6	30.4	1	173.2	123	0.83
P-7	45.9	1.5	302.5	93	0.36
P-8	39.1	1.25	206	123	0.5
P-9	39.1	1.25	521.5	87	0.5
P-10	45.9	1.5	585.5	5	0.36

P-11	30.4	1	57.2	5	0.41
P-12	30.4	1	3,559.60	221	0.41
P-13	23.5	0.75	660.7	239	0.69
P-14	30.4	1	171.4	31	0.28
P-15	18.2	0.5	72.9	185	0.38
P-16	45.9	1.5	469.6	192	0.18
P-17	23.5	0.75	254.4	177	0.46
P-18	18.2	0.5	60.2	57	0.38
P-19	18.2	0.5	5.3	5	0
P-20	18.2	0.5	5.3	5	0
P-21	18.2	0.5	5.3	459	0
P-22	18.2	0.5	5.3	92	0
P-23	18.2	0.5	5.3	69	0
P-24	23.5	0.75	7.2	5	0
P-25	23.5	0.75	7.2	5	0
P-26	23.5	0.75	7.2	5	0
P-27	23.5	0.75	7.2	5	0
P-28	39.1	1.25	11.8	5	0
P-29	30.4	1	9.3	5	0.14
P-30	18.2	0.5	5.3	5	0.38
P-31	23.5	0.75	7.2	5	0.23
P-32	39.1	1.25	11.8	5	0.08
P-33	18.2	0.5	5.3	5	0.38

Appendix G

WaterGEMS with Loop Tree View



Appendix H

WaterGEMS with Loop Solution

Table H1: Pressures in KPa at each junction as modeled in WaterGEMS

Pipe	Diameter (mm)	Diameter (in)	Cost per Section	Length (m)
P-5	23.5	0.75	177.8	123
P-6	30.4	1	173.2	93
P-7	45.9	1.5	302.5	123
P-8	18.2	0.5	91.6	87
P-9	23.5	0.75	318.2	221
P-12	23.5	0.75	264.3	184
P-13	23.5	0.75	660.7	459
P-14	23.5	0.75	132	92
P-15	18.2	0.5	72.9	69
P-23	18.2	0.5	5.3	5
P-24	18.2	0.5	5.3	5
P-25	30.4	1	9.3	5
P-26	18.2	0.5	5.3	5
P-27	23.5	0.75	7.2	5
P-28	18.2	0.5	5.3	5
P-29	30.4	1	9.3	5
P-30	18.2	0.5	5.3	5
P-31	18.2	0.5	5.3	5
P-32	23.5	0.75	7.2	5
P-4	45.9	1.5	453.7	185
P-22	18.2	0.5	5.3	5
P-10	18.2	0.5	250.9	239
P-11	39.1	1.25	72.2	31
P-16	23.5	0.75	276	192
P-18	45.9	1.5	140.5	57
P-19	45.9	1.5	16.4	7
P-17	39.1	1.25	417	177

P-33	30.4	1	9.3	5
P-34	18.2	0.5	5.3	5
P-35	30.4	1	9.3	5
P-1	18.2	0.5	517.6	493
P-2	45.9	1.5	153.3	63
P-3	45.9	1.5	151.2	62
P-21	23.5	0.75	7.2	5
P-20	39.1	1.25	424.8	180

Table H2: Pressure in KPa for each junction as modeled in WaterGEMS.

Junction	Pressure (Kpa)	Junction	Pressure (Kpa)
J-1	125	J-18	153.3
J-2	125.1	J-19	153.2
J-3	187.1	J-20	206
J-4	187.1	J-21	205.5
J-5	153	J-22	41.7
J-6	153	J-23	41.1
J-7	157.5	J-24	17.6
J-8	157.5	J-25	17.5
J-9	168.1	J-26	9.7
J-10	168.1	J-27	135.6
J-11	186	J-28	135.5
J-12	186	J-29	94.4
J-13	66.9	J-30	94.4
J-14	66.9	J-31	102.4
J-15	138.1	J-32	102.4
J-16	137.5	J-33	96.5
J-17	131.1		