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Investigation of Future Flow Reducer Sizes in Houses Added to an Existing Gravity Flow Water System to Ensure its Sustainability

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
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Table of Contents

List of Tables

List of Figures

Abstract

Goal 6 of the United Nations Development Program's new Sustainable Development Goals aims to ensure availability of clean water and sustainable management practices to all by the year 2030. Peace Corps Panama partners with communities in order to help provide sustainable water solutions to communities in need. Water, Sanitation, and Hygiene (WASH) Volunteers spend at least two years living in a community to identify and implement solutions to water problems and train local water committees on how to maintain their improved systems. A common solution for unequal distribution of flow in the distribution network of a gravity flow water system is through the installation of flow reducers before each faucet. These can be sized with the help of NeatWork, a free, downloadable compute software. In Panama, flow reducers (also referred to as orifices) are manufactured to create a perforated plastic diaphragm fitting placed in the distribution pipe or union section upstream of a faucet. They help ensure longevity of the aqueduct by balancing the flows between houses, thus, enabling continuous water flow for all users. An important characteristic of flow reducers is that while they can be installed in new water systems, they can also be installed in existing systems to fix inequalities from inadequate original designs or extensions to the systems. However, little guidance exists for volunteers or communities to ensure the sustainability of these projects. Accordingly, the object of this thesis was to investigate how adding houses to existing aqueducts would affect its serviceability and how to determine a way for communities to size the flow reducers for future houses.

The existing gravity flow water system in Santa Cruz, Panamá was surveyed including all the potential houses which were then analyzed using NeatWork. The results demonstrate that while it is better to include all potential locations during the initial survey, if it expands at an

average growth rate, additional houses may decrease serviceability, but in a negligible way that will not affect the overall reliability of the distribution system.

Utilizing NeatWork, this research showed it is able to determine ideal sizes of flow reducers for additional houses that could be added. Patterns were identified and used to simplify flow reducer sizing so that community members could do it themselves. While most of the time, the ideal flow reducer size for a new house will be the same size as the flow reducer size that is installed in the closest house that is already connected to the aqueduct, sometimes this is not the case. This typically occurs towards the end of branches and in areas where not all flow reducer sizes are present. These areas are clearly identified to the water committee on a map of the distribution system that was provided to various water committee members. With this map and simple instructions, the Santa Cruz water committee can continue correctly adding flow reducers to new houses.

Through the research of this thesis, fabricating and installing flow reducers in the Santa Cruz water distribution system, and working alongside community members many lessons were learned about flow reducers and best practices. This knowledge has been converted into a guide about sustainable flow reducer projects. It has been left with current volunteers and the director of training for the WASH sector of Peace Corps Panama so that the volunteers can adapt the developed tools in their own communities.

Chapter 1: Introduction

1.1 Importance of Potable Water

In 2000, the United Nations (UN) created the Millennium Development Goals (MDGs) to meet the needs of the world's poorest. The importance of clean water is emphasized in Goal 7.C: "Halve, by 2015, the proportion of people without sustainable access to safe drinking water" relative to the year 1990 (United Nations, 2015). Later in 2010, the UN General Assembly declared water a basic human right (United Nations, 2010). Despite the global efforts, in 2015, 663 million people still lacked access to an improved drinking water source with the majority living in rural areas (United Nations, 2015, UNICEF and WHO, 2015).

More work needs to be done to continue increasing water coverage among the poor and to ensure the sustainability of completed water projects. The United Nations Development Program (UNDP) recognizes this and has included water as Goal 6 of the new Sustainable Development Goals (SDGs) that were created in September 2015 to replace the MDGs. Specifically, Goal 6 is to "ensure availability and sustainable management of water and sanitation for all" by the year 2030 (United Nations Development Program, 2015). Other SDGs indirectly depend on access to water.

One way to reduce the 663 million underserved people is by providing piped water on premises, or water that is piped to a dwelling, yard, or plot (UNICEF and WHO, 2015). While this option has been associated with the best health outcomes, only 58% of the world's population currently utilizes piped water (United Nations, 2015, UNICEF and WHO, 2015). However, just because one has access to piped-water does not guarantee they have access to reliable, potable water. For example, water quality is not taken into account when determining if a water system is "improved" and often services are intermittent, creating more health risks

(Schweitzer and Mihelcic, 2012, UNICEF and WHO, 2015). In fact, at a minimum, while still accounting for 8 hours of suspended service, a properly functioning gravity flow water system should operate for 16 hours a day (Schweitzer and Mihelcic, 2012). The World Bank evaluated their water and sanitation projects, which encompass larger and more complicated types of projects such as urban water and sewage systems, that closed between 1990 and 2001 and only 64% were reported to be satisfactory and less than half were deemed likely to be sustainable (World Bank, 2003). Schweitzer and Mihelcic (2012) developed and tested a framework to assess how likely a rural water system in the Dominican Republic was to be sustainable and found that for 18% of the systems, it was unlikely the community will be able to overcome a significant challenge to maintain adequate access to water. Accordingly, it is necessary to continue to improve existing aqueducts and working to make sure communities understand how to maintain and operate their aqueduct systems.

Schweitzer (2009) defined sustainability for a rural community water system as one that provides “1) equitable access amongst all members of a population to continual service at acceptable levels (quantity, quality, and access location) providing sufficient benefits (health, economic, and social) and 2) requires reasonable and continual contributions and collaboration from service beneficiaries and external participants.” Furthermore, the aqueduct should provide water for at least 16 hours per day (Schweitzer, 2009; Schweitzer and Mihelcic, 2012). It is important, to keep the system operating at capacity at all times because people are reluctant to pay for intermittent service and continuous supplies are safer (Lee and Schwab, 2005). Also, increased quantities of water are known to improve health through providing access to improved sanitation and hygiene (Mihelcic et al., 2009) and can specifically reduce diarrhea by 20-25% as it allows for better hygiene practices (Fry et al., 2010).

1.2 Gravity Flow Aqueducts

Gravity flow water distribution systems (also referred to as aqueducts) are an appropriate way to provide developing communities piped water. Typically, they have low operation and maintenance associated with them since no mechanical energy (e.g., via pumps) is required (Mihelcic et al., 2009). A typical gravity flow system collects water from the source, a spring or river, through an intake structure. It is then carried through a conduction line into a storage tank. From the tank, water flows into the community through a distribution network which can have multiple branches that end at faucets. These faucets provide the users with their basic water needs. More information about the design and construction of each component can be found *in A Handbook of Gravity-Flow Water Systems* (Jordan, 1984) and *Field Guide in Environmental Engineering for Development Workers* (Mihelcic et al., 2009). There is also much detail in the many research documents generated by the Master's International Peace Corps Program (e.g., Reents, 2003; Niskanen, 2003; Simpson, 2003; Annis, 2006; Good, 2008; Schweitzer, 2009; Suzuki, 2010; Orner, 2011: Yoakum, 2013). These resources suggest the engineer would rely primarily on placement of different size pipe combinations and globe valves to obtain the appropriate amount of water at each tapstand. However, there is very little information found in this and other literature on how to properly use flow reducers in a rural gravity flow water system.

1.3 Water Access in Panama

Panama has a large wealth distribution as shown by the relatively high GINI index of 51.9 where 0 represents perfect equality and 100 represents total inequality (World Bank, 2014). Furthermore, 27% of the population is living in poverty (CIA, 2014) and 14.2% are living in extreme poverty (Guillén, 2012). In contrast, 98% of the country's population has access to an improved water source (UNICEF and WHO, 2015). Unfortunately, this percentage decreases to 89% in rural areas (UNICEF and WHO, 2015). Furthermore, the worst coverage rates in Panama are found in the indigenous rural areas where only 47.6% of people have potable water (Guillén, 2012)

Gravity flow water systems are one type of improved water source being used in Panama (Guillén, 2012). Panama's mountainous geography and abundant rainfall during the rainy season make it a likely place for gravity flow aqueduct systems. This is one reason why almost all of Panama's rural populations with a safe-water source (89%) have piped water on premise (83%) (UNICEF and WHO, 2015).

These water systems are maintained by local governing bodies formally known as Juntas Administrativas de Acueductos Rurales (JAAR) which translates to the Administrative Boards of Rural Aqueducts. However, they are more commonly referred to as Directivas in Spanish or Water Committees in English. They consist of seven elected people from the community who are responsible for the administration, operation, and maintenance of the aqueduct (MINSA, 1994). While these people are responsible for ensuring the sustainability of the aqueduct, no technical experience is required (MINSA, 1994).

1.4 Peace Corps in Panama

The Peace Corps started working in Panama in the Environmental Health sector, now renamed Water, Sanitation, and Hygiene (WASH) in 2002. Since its creation, more than 215 Peace Corps Volunteers have served in communities working towards the following objectives: 1) train community members to increase participation, organization, and capacity for sustainable projects, 2) educate community members to prevent water borne disease transmission, 3) train water committees how to operate, maintain and manage potable water and sanitation systems, and 4) construct, improve, or rehabilitate water systems (Redmond, 2012).

1.5 Peace Corps Master's International Program

Peace Corps Volunteers are now able to combine their training and service with graduate education through Master's International (MI) (Mihelcic et al., 2006; Hokanson et al., 2007; Mihelcic, 2010; Manser et al., 2015). The author of this thesis was enrolled in a Master's International program and that particular program requires a research thesis as part of the graduate degree requirements. Examples of water-related research theses performed by Peace Corps Volunteers in Panama include *Embodies Energy Assessment of Rainwater Harvesting Systems in Primary School Settings on La Peninsula Valiente, Comarca Ngöbe Bugel, Republic of Panama* (Green, 2011), *Post-Project Assessment and Follow-Up Support for Community Managed Rural Water Systems in Panama* (Suzuki, 2010), *Effectiveness of In-Line Chlorination of Gravity Flow Water Supply in Two Rural Communities in Panama* (Orner, 2011), *Improving Implementation of a Regional In-Line Chlorinator in Rural Panama Through Development of a Regionally Appropriate Field Guide* (Yoakum, 2013), *Evaluation of Hand Augered Well Technologies' Capacity to Improve Access to Water in Coastal Ngöbe Communities in Panama* (Hayman, 2014). Other MI students have completed research to access the sustainability of development projects focused on water and sanitation that have been published as journal articles (Schweitzer and Mihelcic, 2012; McConville and Mihelcic, 2007). A full list of reports and theses created by MI students can be found online on the University of South Florida's Master's International Website (University of South Florida, 2014).

1.6 Flow Reducers

As mentioned previously, Peace Corps Volunteers in Panama work on a variety of different projects to increase water coverage in their communities. One typical improvement is installing flow reducers (also referred to as orifices and discs) in a gravity flow water system. Flow reducers help ensure longevity of the aqueduct by balancing the flows between houses, thus, enabling continuous water flow for all users. In this particular context, flow reducers consist of a “perforated plastic diaphragm fitting in a pipe or union section (whose diameter is normally a nominal 1/2 inch) upstream of a faucet” (Agua Para la Vida, 2010).

Holes of different sizes are drilled into the flow reducers and the flow reducers are installed strategically throughout the system. Houses at lower elevations and/or close to the tank will receive a flow reducer with a smaller hole, creating a larger headloss, thus making it more difficult for the water to arrive. Houses at higher elevations and/or far away from the tank will receive flow reducers with a larger hole or will not need a flow reducer at all. This will create a smaller headloss or none at all. With all the flow reducers installed the available head at each house is expected to be similar allowing water to flow equitably to all faucets.

Peace Corps volunteers in Panama are trained on a free software program called NeatWork to size the flow reducers. It was created by Agua Para La Vida, an NGO working on gravity flow systems in Nicaragua. More information about Agua Para La Vida can be found online at apvl.org (Agua Para La Vida, 2014). NeatWork was designed by engineers and scientists who work in the United States and France and was tested on a variety of Nicaraguan gravity flow aqueducts. It is freely offered to other NGOs and the Peace Corps to assist with the design of gravity flow aqueducts. It can be downloaded online from the NeatWork homepage (Agua para la Vida and ORDECSYS, 2010). The design principles of NeatWork and how to size flow reducers with this software are explained in Section 2.2. Using NeatWork to size flow reducers, many Peace Corps Volunteers have successfully implemented flow reducer projects with both new and existing aqueducts.

Flow reducers need to be located close to the faucets (i.e., tapstand) to produce a localized effect instead of placement in the pipe close to the main line in the distribution network as this might affect multiple faucets at once (Agua Para La Vida, 2010). However, Agua Para La Vida does not provide specific distance requirements providing an ideal distance away from the faucet or away from the main line in the distribution network. In a new gravity flow water system, the flow reducers can be placed in the male end of a pipe connection. When adding flow reducers to an existing water system, the pipe can be cut and reconnected with a union placing the flow reducers on the upstream side. Both ways of installing a flow reducers are depicted in Figure 1.

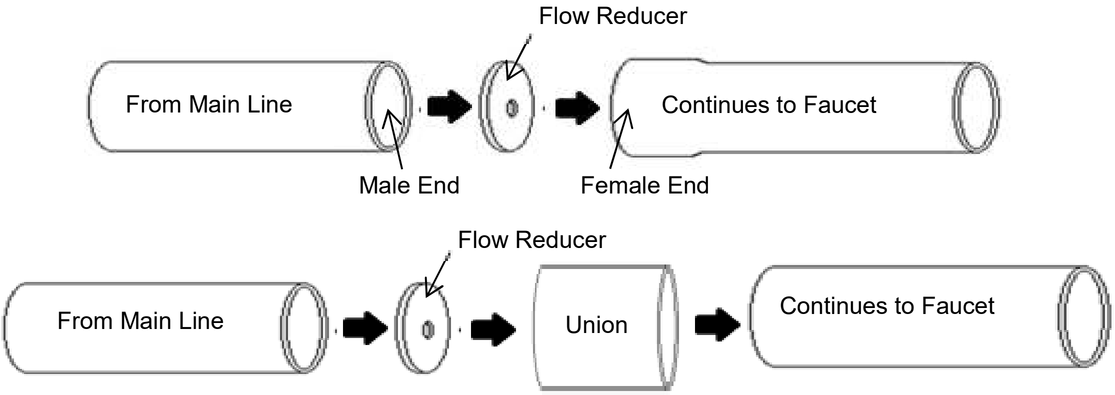


Figure 1: Schematic of How and Where a Flow Reducer is Installed in a Pipe

Flow reducers can be inexpensively fabricated from PVC pipe. For example, out of about 2-m of 2.5-inch PVC pipe found in the community, the author was able to fabricate all the required flow reducers for the aqueduct as well as additional flow reducers to leave with the water committee to use in future connections. The other tools and materials needed to make the flow reducers were either borrowed from community members or purchased locally for less than $25. More information regarding flow reducers including detailed instructions on how to manufacture them can be found in Appendix A. The author of this thesis wrote this guide for future Peace Corps Volunteers based on her experience and research for this thesis.

While NeatWork helps to size flow reducers, Agua Para La Vida does not provide information on how to ensure the projects are sustainable. For example, they do not talk about how aqueduct expansion might affect serviceability or how to size flow reducers as new houses are added to the system. The two key books for the design of gravity flow systems in the developing world, *A Handbook of Gravity Flow Water Systems* (Jordan, 1984) and *Field Guide in Environmental Engineering for Development Workers* (Mihelcic et al., 2009), also do not mention flow reducers. Without the use of flow reducers, it is harder to ensure an equal distribution of flow on large aqueducts. Without instructions for aqueduct expansion for systems that use flow reducers, it is difficult to guarantee the project's sustainability.

1.7 Background Information on Intended Santa Cruz Aqueduct

The author of this thesis worked for almost two years in Santa Cruz, a rural community in the province of Coclé, Panamá located in Figure 2. Before her arrival, there were two community aqueducts and various independent systems. The majority of the community wanted a connection to the community aqueduct, which was undersized. With the support of the community, she performed a topographical survey of the system and was able to design a new robust principal aqueduct with a larger storage tank and a distribution line that could serve 73 houses of the community. However, only 60 of these houses expressed interest in an immediate connection. The locations of key elements for the new aqueduct are shown in Figure 2 (Google Maps, 2016).

Previously in the community, for each new connection the owner was required to pay US$15 to the water committee and buy all their own materials. This rule was left in place even with the expansion project to ensure fairness to those houses that recently installed their own connections. This cost however deterred some families from committing to the new project. One reason for this was because many houses in this community are occupied by sons or daughters that recently moved out of their parents' house but still live next door. They are thus used to obtaining their water from their parents' house. Others are used to maintaining their own independent water systems and while the source may not be well protected or treated, the owners are content with their current water situation. In addition, some houses are still under construction so the owners do not see an urgent need to add a water connection. Therefore, 13 houses did not immediately plan to connect to the aqueduct, but may in the future. The layout of the aqueduct and locations of the 60 confirmed household connections and the 13 potential future connections are displayed in Figure 3. The system shown in Figure 3 is the system that the author analyzed, designed the necessary improvements, and solicited the required money to redo the distribution line. The numbers in the figure represent the faucet numbers for both the confirmed and the potential houses to be added in the future.

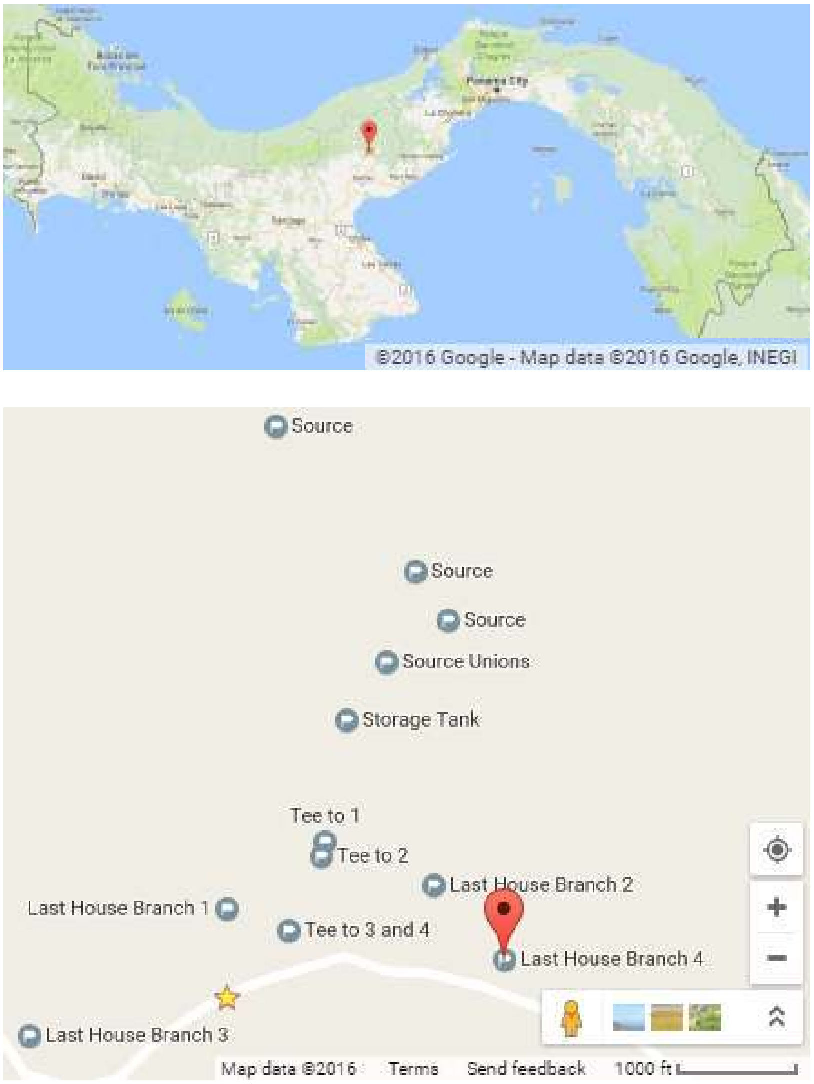


Figure 2: Map Showing where Santa Cruz is Located within Panama and where Key Aqueduct Components are Located within Santa Cruz.

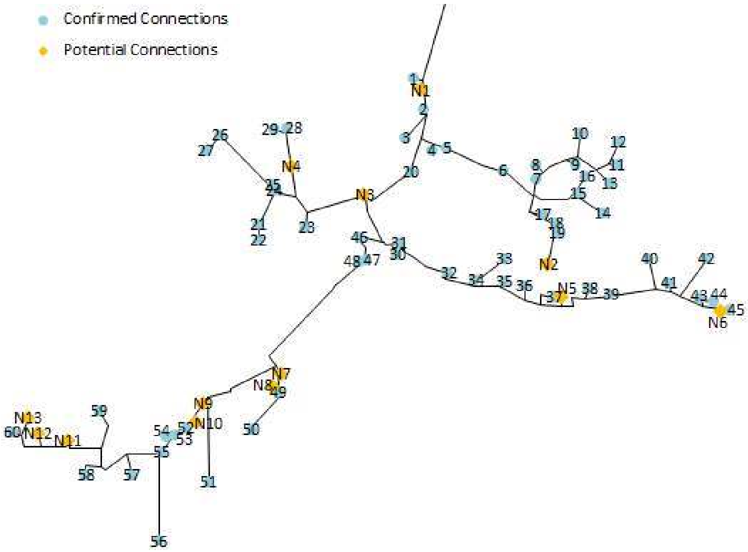


Figure 3: Map of Confirmed Connections and Potential Connections with Faucet Numbers for Santa Cruz Aqueduct (not to scale)

1.8 Motivation

To remain sustainable, the aqueduct should provide water for at least 16 hours per day (Schweitzer and Mihelcic, 2012). It is important to keep the system operating at capacity at all times, because people are reluctant to pay for intermittent service and continuous supplies are safer (Lee and Schwab, 2005). Also, as mentioned previously, increased quantities of water can reduce diarrhea by 20-25% as it allows for better hygiene practices (Fry et al., 2010). The flow reducer projects are an inexpensive and appropriate technology to regulate flows between houses of new and existing aqueducts. However, during the life of an aqueduct (estimated to be 20-25 years (Jordan, 1984), communities can grow in size and houses are added to the aqueduct. It is thus necessary to provide the newly added houses the proper size flow reducer in order to guarantee that the flows are maintained at each existing household in the system. This will promote the sustainability of the aqueduct as it will help maintain a constant flow to the houses. If the basic flow is not maintained correctly it is possible that in time the level of service will fall below a level that protects human health.

Gravity flow water systems consistently fall into disrepair because communities do not feel responsible for maintaining the system or they do not have the capacity to sustain them (Breslin, 2003). Currently, flow reducer projects may set a community up for failure because tools are not available for the local water committee to continue maintaining the project into the future. While it would be easy for a Peace Corps Volunteer to remodel the aqueduct with the additional or removal of houses in NeatWork to determine the required flow reducer sizes, this is not a realistic task for a community water committee. This can create a problem because at the most, communities work with Peace Corps Volunteers for 6 years, which is shorter than the 20-25 year assumed life of an aqueduct. Accordingly, one volunteer suggested to his water committee to size new flow reducers by using the same diameter of that used in the house closest to it on the distribution line. This may work if houses are located close together, but in many communities, houses are spread out over long distances so this may not be an ideal recommendation. Therefore, an analysis of water systems needs to be performed in order to better equip the water committees with information to determine the correct size of a flow reducer without the use of computer software. Also, guidelines for future Peace Corps Volunteers and other development workers should be developed to help them implement sustainable flow reducer projects.

1.9 Objectives

The previous information shows the importance that the correct sizing of flow reducers during aqueduct expansion could have in ensuring the health benefits of current and future users of a gravity flow water system. However, there are currently no guidelines on how to promote their continued use. Accordingly, the objectives of this research are to:

1) Use the NeatWork model to determine how the addition of houses to an existing gravity flow water system will affect its serviceability.

2) Develop an easy to understand method to teach community members from Santa Cruz (Panama) in order to enable community members to correctly size flow reducers for houses added to the water system in the future.
3) Provide guidance to future Peace Corps Volunteers and development workers to ensure they are able to design and implement sustainable flow reducer projects in their respective communities.

Chapter 2: Literature Review

2.1 Aqueduct Design

The author researched aqueduct design based on foundational fluid mechanics as well as accepted practices used for designing aqueducts in the developing world. She also investigated available computer software to aide in the design. Particular emphasis was placed on the understanding of the software Neatwork because this is the program most used by Peace Corps Volunteers in Panama.

2.1.1 Fluid Mechanics Related to Thesis Research

In order to design a pipe distribution network, the designer must collect information that includes flow rates, elevations of the storage tank; the locations of houses being served, and the topographical profile in-between pipe segments along with the horizontal distances of each segment of pipe. All this information is required to ensure each house or tapstand has sufficient water pressure while also eliminating areas of low pressure.

Pipe size in a gravity flow water system can be determined using an iterative approach based on the Darcy-Weisbach Equation (Equation 1) and the Moody diagram (Crowe et al., 2010). The iterative approach is necessary because pipe sizes are dependent on a friction factor that varies with diameter.

$$h_L = f\,\frac{\mathrm{L}}{\mathrm{D}}\frac{\mathrm{v}^2}{2g} \qquad (1)$$

In Equation 1,

h_L = headloss (m)

f = friction factor (unitless)

L = length of pipe (m)

D = pipe diameter (m)

v = *velocity through pipe (m^2/s)*

The engineer can determine allowable headloss, length of pipes, and flows from a topographical survey of the system and water needs. Because both the friction factor and the pipe diameter are unknown during the design stage, one can assume a friction factor (f) (which is based on the pipe material and age) and calculate a pipe diameter based on that value. Then a designer would use that diameter (D); the Reynolds number (Re); and the relationship between friction factor and the Reynolds number and the diameter as defined by the Moody diagram or Equation 2, to calculate a new friction factor (Crowe et al., 2010). Using the newly calculated friction factor, one should repeat the process until the assumed friction factor matches the calculated friction factor.

$$f = \frac{0.25}{\left[log_{10}\left(\frac{k_s}{3.7D}+\frac{5.74}{Re^{0.9}}\right)\right]^2} \qquad (2)$$

In Equation 2,

k_s = roughness of various pipes (1.006×10^{-7} m for PVC converted from Mihelcic et al. 2009)

In order for the assumed friction factor and the calculated friction factor to match, the pipe diameter will most likely be an unrealistic value rather than a standard pipe size. Thus a user would select the diameter of the next largest pipe size available and verify that requirements are met using the Bernoulli's Energy Equation (Equation 3) and the hydraulic grade line (HGL) (Crowe et al., 2010). The Bernoulli Equation represents the amount of energy a fluid has which can be expelled in three forms: pressure, velocity, and elevation. The total amount of energy stays constant in a system as long as head losses are taken into account:

$$\frac{P_1}{\gamma} + \frac{{v_1}^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{{v_2}^2}{2g} + z_2 + \Sigma h_L \qquad (3)$$

In Equation 3,

P = *pressure* (N/m^2)

γ = *specific weight of fluid* (N/m^3)

v = *velocity* (m/s)

g = *gravitational acceleration* (m/s^2)

z = *elevation*

Σh_L = *sum of the headloss*

The HGL is the energy line representing the total amount of hydraulic head at any given point in the system. To calculate the total head at any point, one can use the right hand side of the Bernoulli Energy Equation. Typically, the HGL is represented graphically along with the topographical profile of the land to visually inspect that there is adequate pressure throughout the entire system. A sample HGL for a rural gravity flow water system is shown in Figure 4.

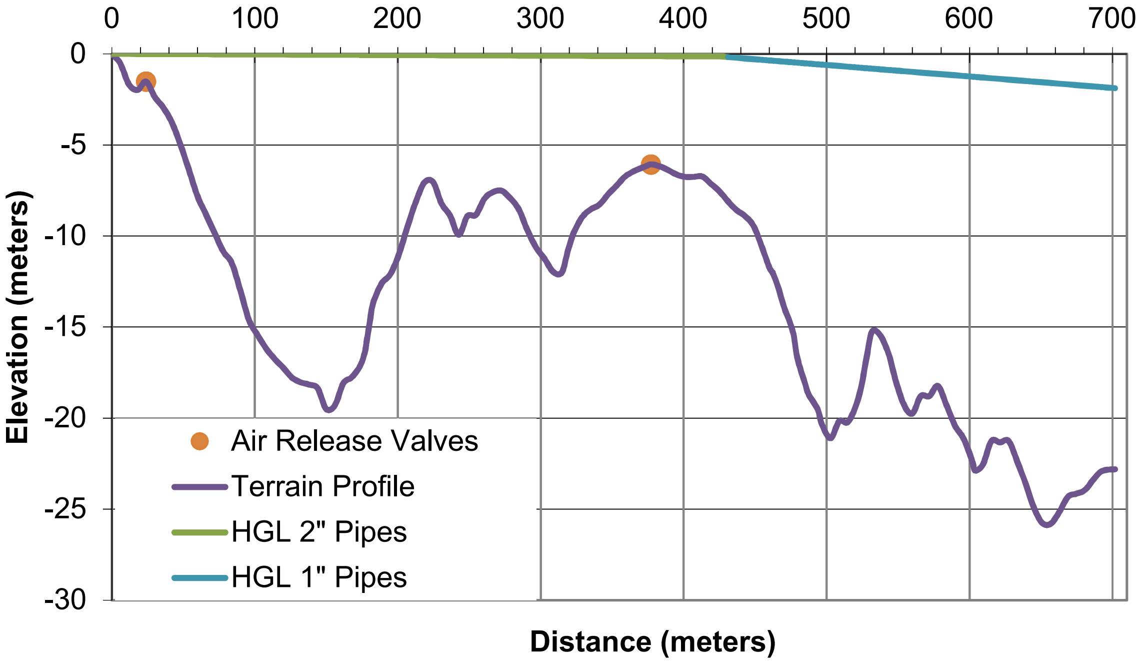


Figure 4: Sample Hydraulic Grade Line (HGL)

Major losses or frictional losses in the pipes are shown by the slopes of the HGL. When flows are equal, smaller pipes have higher frictional losses and therefore have steeper slopes in the HGL. Minor loses from placement of pipe fittings that include reductions and elbows can also be included in a HGL and are represented by vertical drops. Minor losses can be calculated from Equation 4 using the minor loss coefficient (K) as presented in Table 1 (Crowe et al., 2010).

$$h_{Lminor} = K\frac{v^2}{2g} \tag{4}$$

In Equation 4,

h_{LMimor} = *headloss (m)*

K = minor headloss coefficient (unit less)

v = velocity through component (m^2/s)

Table 1: Minor Headloss Coefficients (K) for Various Aqueduct Components Obtained from Crowe et al. (2010)

Type of Component		**K**
Globe Valve-Wide open		10.0
Tee-straight through flow		0.4
Tee-side outlet flow		1.8
90° elbow		0.9
45° elbow		0.4
Reductions d_1 is the diameter of the larger pipe and d_2 is the diameter of the smaller pipe	d_2/d_1	
	0.2	0.49
	0.4	0.42
	0.6	0.27
	0.8	0.2
	0.9	0.1

These head losses are usually minor in a gravity flow water system compared to that of the frictional loses through the pipe. For this reason, they are normally ignored in the design of distribution networks. Mihelcic et al. (2009) states that it is especially important to consider the frictional loses of the elbows at a tapstand where remaining pressure can be low and several fixtures can make up the tapstand construction (Mihelcic et al., 2009).

Orifices (such as a flow reducer) are more commonly used to measure flows, but can also be used to create a large drop in head. The headloss through an orifice can be calculated using Equation 5 (Crowe et al., 2010):

$$\mathrm{Q} = CA\sqrt{\mathrm{2gh}} \tag{5}$$

In Equation 5,

Q = flow (m^3/s)

C = coefficient of orifice (unitless)

A = cross sectional area of orifice (m^2)

g = gravitational acceleration (m/s^2)

h = headloss through orifice (m)

Solving Equation 5 for headloss results in:

$$h = \frac{\mathrm{Q}^2}{\mathrm{C}^2 A^2 2g} \tag{6}$$

The head loss determined from Equation 6 that results from the placement of an orifice (e.g., flow reducer) in a gravity flow water system will not be negligible and should be included when calculating the HGL.

Globe valves can also be used to regulate flows through a gravity flow water system. Globe valves have a spherical shape that is split by an internal baffle. It has a handle and stem that can be rotated various times to adjust the flow that is able to pass through it as well as a plug to completely stop flow. Even when the globe valve is fully opened, it creates a large headloss. This headloss can be calculated using an adaptation of Equation 4 and the coefficient for minor losses associated with globe valves presented in Table 1 resulting in Equation 7:

$$h_L = 10\frac{v^2}{2g} \tag{7}$$

2.1.2 Water Distribution Systems in the Developed World

A water distribution system (WDS) in the developed world consists of sources, pipes, tanks, water towers, and hydraulic control elements including pumps, valves, and regulators (EPAa, 2014, Ostfeld et al., 2002). These systems are designed to provide uninterrupted, pressurized, and safe drinking water to all its consumers (EPAa, 2014). In order to provide uninterrupted flow, modern systems depend on loops in the design to create redundancy in the system (Mihelcic and Zimmerman, 2014).

The design of looped systems can be performed using the Hardy-Cross method which is an iterative approach changing flows throughout the system until continuity is satisfied at all junctions (Crowe et al., 2010). However, it is more common to use computer software. Some of the computer software commonly used in the developing world to design looped water distribution systems are described in Table 2.

Table 2: Summary of Computer Software for the Design of Distribution Networks Used in the Developed World

Program	Description and Capabilities	Cost	Source
EPANET	• Models water movement and quality within a pressurized network • No limit on system size • Incorporates pumping and storage tanks of different shapes and sizes while considering different demands at nodes that vary with time	free	EPA, 2014b
InfoWater	• Integrates advanced hydraulic modeling and optimization with ArcGIS™ • Design, optimization, area isolation, water quality, particle build-up, scheduling, and maintenance tools	$1,000-$14,000 depending on linkages	Innovysze, 2014

Table 2: (Continued)

WaterCAD V8i	• Models hydraulics, operations, and water quality to help analyze, design, and optimize water distribution systems • Water-age, tank-mixing and source-trace analysis to develop comprehensive chlorination schedules, simulate mock contamination events, model flow-paced and mass-booster stations, visualize zones of influence for every water source	Dependent on number of pipes 10 pipes- $202 500 pipes - $3,101	Bentley, 2014
SynerGEE Water	• Simulation package used to model and analyze water distribution networks • Pipe design, area isolation, calibration, customer management, reliability analysis, and subsystem management modules. • Extended period analysis with cost of controls and pressure-dependent demand	Depends on size and licenses desired	DNV GL, 2013

Studies are being done to evaluate the reliability of urban water distribution systems; however, the calculations are computationally expensive and therefore undesirable for some iterative design approaches (Atkinson, 2013). While some of the optimization tools are being applied to gravity flow distribution systems (Reca et al., 2008) and it is recommended to use loop networks whenever possible in the developing world (Water for the World, 2005), often, these are not appropriate technologies. Adding loops increases the number of pipes needed. Using pumps increases cost and maintenance and may be infeasible in numerous communities without electricity. Therefore, comparing gravity flow distribution networks to urban distribution networks is out of the scope of this thesis.

However, information generated from studies conducted on urban water distribution systems can be applied to the gravity flow systems studied in this research even if mechanical energy is not being used. For example, Santana (2015) and Santana et al. (2014) studied the embodied energy use of water distribution systems in Tampa (Florida) for various development use patterns and repair on the infrastructure. That study determined that energy savings can be made by planning urban growth to avoid the extra energy needed to transport the water farther distances. In gravity flow distribution networks all the energy comes from gravity, thus extra energy will not be required, but placing new houses closer to the existing distribution system will ensure that there is enough potential head for new houses to have adequate pressure.

In addition, over time, scale build up on pipes creating greater friction losses that require greater energy use. Leaks in the system also require more water to be pumped through the system to maintain the same pressure. Maintaining piping infrastructure can thus minimize the embodied energy primarily though minimizing leaks and partially through minimizing build-up (Santana, 2015). Minimizing leaks in a gravity flow distribution is thus important to ensure equal distribution and an adequate water supply. NeatWork incorporates scale build up on pipes into its calculations and uses a friction factor 4.5% greater than that of a smooth PVC pipe (Agua Para la Vida, 2010). However, it is currently unknown how long it takes for a PVC pipe to reach this higher friction factor.

2.1.3 Water Distribution Systems in the Developing World

Most developing world systems are trees or branched networks meaning water can only reach each tapstand through one path (Mihelcic et al., 2009). Two books exist to provide guidance on the design of branched systems in the developing world: *A Handbook of Gravity-Flow Water Systems* (Jordan, 1984) and *Field Guide in Environmental Engineering for Development Workers* (Mihelcic et al., 2009). Jordan's (1984) handbook was written based on construction of numerous rural systems in Nepal with public faucets. Mihelcic et al.'s (2009) field book is based on the experience of many Peace Corps Volunteers and graduate students.

Also, as mentioned previously, there are also numerous research reports/theses developed through the Master's International Program in Civil & Environmental Engineering related to gravity flow aqueduct design and construction (Mihelcic et al., 2006) that are summarized in Table 3.

Table 3: Summary of Relevant Master's International Reports and Theses on Design and Construction of Gravity Flow Water Systems

Source	Relevance
Good, 2008	• Microsoft Excel spreadsheet designed to help development workers make project designs over the entire life of the project called GOODwater • Recognizes that projects need to have low capital costs • Allows to design for different level of services • Incorporates sustainability factors • By hand difficult to obtain optimized results wasting capital resources • Criticizes NeatWork for not addressing sustainability issues and being limited in scope • No mention of creating equal flows between faucets or use of valves
Annis, 2006	• Assess systems ranging from 1 to 12 faucets (typical between 4 to 7) • Most water shortages from lack of maintenance rather than lack of water • Little mention of design of systems
Niskanen, 2003	• Uses PVC rigid pipe friction loss tables and plotting the correspond HGL to determine pipe size • No use of orifices or globe valves to regulate flows between houses • Two houses had gate valves installed to prevent the excessive pressure from breaking the taps (in hind sight says a better solution would have been an additional break pressure tank) • Community perception desired 2-inch tubes throughout the entire system
Reents, 2003	• Uses spreadsheet created by Peace Corps Honduras for design (only works with branched systems) • States if possible, looped systems should be used to create equal pressure

Table 3: (Continued)

Simpson, 2003	• Proper tube sizing is most important factor, but can also use control valves to regulate flows between houses • Looped systems will reduce headloss since two pipes will carry the same amount of water at lower flows • Discourages daily sectorization as it encourages families to collect water making the peak flow higher than the flow used in the design • Community perception is that smaller tubes bring better pressure

Both books described above use procedures for the design of gravity flow aqueducts based on Bernoulli's Equation, the Darcy-Weisbach Equation, and HGLs. The books show how to determine the velocity through the pipe by the end user demand assuming all the faucets are open. The flow at each faucet is determined and the flow through each pipe is then back calculated so that the flow going into any junction is equal to the sum of the flows leaving this junction (Mihelcic et al., 2009). Once the flows are determined, the designer can plot the required HGLs and correctly size the pipes in the distribution network.

Simplified ways to design distribution systems are being created and utilized. When the diameter and flows are known, the friction factor can easily be calculated. Faiia (1982) calculated various frictional factors and presents them in “Rigid PVC Frictional Headloss Factors”. Similar tables can also be found online at The Engineering Toolbox (2016). This method allows designers to use a more visual trial and error approach to select pipe sizes by selecting values from the table and then plotting the HGL. Spreadsheet programs are also being created for development workers to use that automatically calculate many factors for the user (Reents, 2003: Simpson, 2003). Some development workers are using software such as EPANET (Simpson, 2003) and NeatWork for the design as well.

To regulate flow through the system, Jordan (1984) suggests the use of globe valves placed near the discharge points. These valves are adjusted to permit the preferred quantity of water to pass through when all the taps are opened. While Jordan recognizes that the flows will change depending on what combination of taps is opened, he states the fluctuations are negligible.

Orifices are not mentioned by either Jordan (1984) or Mihelcic et al. (2009) as a way to equalize flow between houses. However, Jordan (1984) does mention orifices (referred to as frictional diffusers) as a way to minimize pressure at faucets with pressures exceeding the pressure limits. He also provides an orifice design using a 3-mm nail to melt a hole through an end cap that can be placed in the pipe just upstream of the tapstand. The flow through this specific orifice can be related to the head loss by the following equation (Jordan, 1984):

$$h_L = 369Q^2 \tag{8}$$

In Equation 8,

h_L = headloss through the orifice (m)

Q = flow through the orifice (L/s)

Careful observation shows that Equation 8 is a simplified version of Equation 5. Jordan (1984) assumes that the orifice coefficient is 0.6 and the diameter made from a 3-mm nail is approximately 5 mm and has an area of 1.96 x 10-5 m^2. When these values are placed into Equation 5 along with a conversion to use flow in units of L/s (instead of m^3/s) results in a constant of 367.2. With the target flow rate of 0.2 L/s, Equation 5 and 8 provide headloss that results in a 0.47% difference in headloss with Jordan's calculation (Equation 8) being slightly larger.

Chapter 12, "Increasing Capacity of Existing Gravity-Fed Water Systems" (Mihelcic et al., 2009), provides more information on inequality of flows between houses explaining that the HGL drops faster when more houses have taps open. This means that houses close to the HGL may receive water at some points during the day, but they receive less when other taps are opens and sometimes no water at all. It also suggests the use of globe valves, to limit the flows to the houses farther from the HGL. However, that chapter does not provide detailed information in the determination of where or how to correctly limit these flows, but states that "case-by-case examination of each system must be made for the proper installation of valves" (Mihelcic et al, 2009).

Both Jordan (1984) and Mihelcic et al. (2009) rely on the HGL in the design of the distribution network of a gravity flow water system. From the HGL, one can determine pipe sizes to ensure adequate pressures throughout the entire network as well as avoiding negative pressure regions. The maximum pressure depends on the type of pipe. In Panama, most systems are constructed out of PVC, which has a maximum pressure limit of 100-m of head (Mihelcic et al., 2009). More importantly, the HGL will provide the pressure at each tapstand. This ensures that there is a reasonable amount of pressure for the user, while preventing excessive pressures that can break the faucets. Minimum and maximum pressures vary between sources and are summarized in Table 4.

Table 4: Recommended Maximum and Minimum Pressure at Faucets in a Gravity Flow Distribution System

Source	Minimum (m)	Maximum (m)
Mihelcic, 2009	10	--
Jordan, 1984	7 10 desired	15 desired 30 desired cap 56 absolute
Water for the World, 2005	7	15-20

These guidelines are based on functionality, but designing a system of equal pressure at each faucet would also create more equal flows. Target flow rates for a gravity flow water system at each faucet are summarized in Table 5.

Table 5: Recommended Maximum and Minimum Flow Rates at Faucets in a Gravity Flow Distribution System

Source	Flow Rates (L/s)
NeatWork	0.1 Minimum 0.2 Desired 0.3 Maximum
Jordan, 1984	0.2 minimum 0.225 desired
Water for the World, 2005	0.03 minimum 0.23 maximum

Another important consideration of aqueduct design, is designing for the future so that the aqueduct continues to function. As mentioned previously, normally the design life of a gravity flow water system is assumed to be 20-25 years (Jordan, 1984). While both Jordan (1984) and Mihelcic et al. (2009) mention this and determine required flows based on the design population using a future population calculated using Equation 9 for populations under 2,000 people (Mihelcic et al., 2009), neither details how to adjust the design of the system for future expansions.

$$P_N = P_O * \left(1 + \frac{r \times N}{100}\right) \tag{9}$$

In Equation 9,

P_N = *the future population*

P_0 = *the current population*

r = *rate of growth*

N = *number of years*

Focusing on the future water requirement does not pose a problem to the users if they are using communal taps and the additional population stays fairly centralized. However, it may create a problem if faucets are added. Jordan (1984) suggests that the designer of the original system can predict where future faucets may be added, design accordingly, and leave instructions on where future faucets should be located. In Panama, where most systems provide piped water directly to the individual houses it is not feasible to expect an author to determine locations of all connections during the original design phase.

Suzuki (2010) assessed 28 water systems in Panama that Peace Corps Volunteers had worked on. Of these, 17 were brand new systems and 11 were repaired. While he assessed numerous characteristics, the relevant one for the research in this thesis is the distribution line. Suzuki recognized there was inequality in flow between houses with those at a higher elevation and farther away from the tank receiving less water, and this problem was made worse when additional household connections were added to the system without proper design. He also observed that the houses with leaky taps from excess pressure have little incentive to repair the leaks as they are the last households to experience water shortages. The criteria used by Suzuki to rank the distribution lines and the resulting distribution of ratings he determined by his assessment are presented in Table 6 and Table 7.

Table 6: Suzuki's (2010) Ranking Criteria for a Distribution Lines

Score	Score Description
1	Leaky or broken taps, no valves, major inequity of water pressure and flow, exposed and leaky tubes
2	Leaky or broken taps, no valves, some inequity of water pressure and flow, exposed and leaky tubes
3	Some leaky or broken taps, control valves, some inequity of water pressure and flow, exposed tubes, minimum leaks
4	Adequate pressure and flow at all houses, control valves, very little leaky or broken taps, tubes buried, minimum leaks
5	Adequate pressure and flow at all houses. Physical infrastructure is intact including; faucets, service line control valve, main line control valves,

Table 7: Distribution of Results from Suzuki (2010) Study for Distribution Lines

Score Range	Distribution
4 to 5	61.5%
2.5 to 3.5	30.8%
1 to 2	7.7%

Table 7 suggests that 38.5% of the Panamanian systems evaluated by Suzuki (2010) were already in need of some repair to the distribution line (rating scores of ≤ 3.5) when the average system is only 4 years old. This means it is necessary to provide a water committee with more maintenance training and materials (Suzuki found that few communities possessed any sort of operator's manual) or the communities will need more outside assistance possibly in the form of a circuit rider as suggested by Suzuki (2010).

While most communities requested continued outside assistance (Suzuki, 2010) and circuit riders now exist in Panama as Peace Corps Response Volunteers, the preferred method is to increase capacity by providing better training. For this thesis research, the idea of training water committees on how to size and install their own flow reducers is feasible if proper design tools and training are provided.

2.2 NeatWork and its Design Principles

The two primary features of NeatWork, a free software program that aids in the design of distribution system, (Agua Para La Vida, 2010) are a design optimization and a simulation phase. NeatWork optimizes networks and runs its simulations accounting for friction in the pipes according to the Darcy-Weisbach Equation and the Reynolds number. NeatWork also aims to minimize the cost of the system because cost is a major constraint in the construction of gravity flow water systems. Designing systems based on the assumption that all faucets are open is excessive because not all faucets need to be opened at the same time. Therefore, NeatWork simulates the flows through systems with a user-defined fraction of faucets opened to ensure that the flow of each faucet varies only within acceptable bonds.

2.2.1 Design Phase

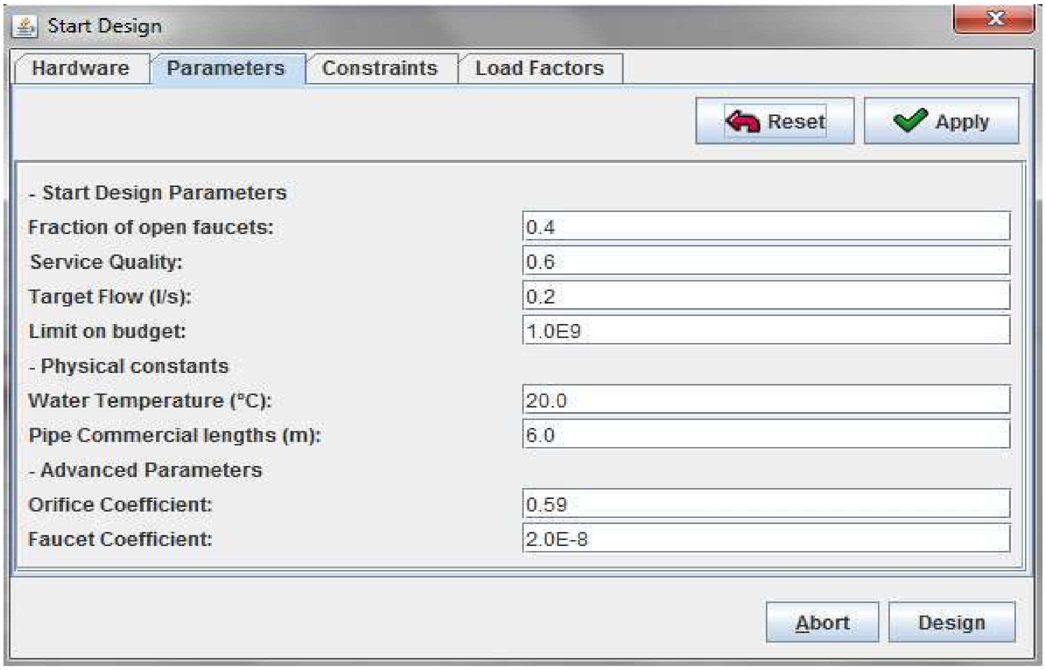
The design optimization phase of NeatWork creates a design of an aqueduct or an expansion to an existing aqueduct based on user inputs. This serves as a starting point for a design that can later be improved upon in the simulation phase. The inputs and outputs for the design phase are presented in Table 8 with the default parameters shown in Figure 5.

Table 8: Input and Output for NeatWork's Design Phase

Inputs	Outputs
Node List: ID, height, X and Y coordinates[1], number of faucets, and nature (i.e., tank, node, or tap)	Ideal orifice size
Arc List: Begin ID, End ID, and Length	Commercial orifice size
Types of pipes that can be used	Diameter of pipe[2]
Constraints on pipe sizes for specific arcs	
Orifice diameters that can be installed	
Parameters	
Modified Load Factors	

[1] The X and Y coordinates can be used for advanced features. If there is no plan to use these features, entering 0 for all of them does not affect the design.

[2] Sometimes a segment will be broken into two different diameters. In these cases, the lengths of each segment are provided as well.



- Start Design Parameters
Fraction of open faucets: 0.4
Service Quality: 0.6
Target Flow (l/s): 0.2
Limit on budget: 1.0E9
- Physical constants
Water Temperature (°C): 20.0
Pipe Commercial lengths (m): 6.0
- Advanced Parameters
Orifice Coefficient: 0.59
Faucet Coefficient: 2.0E-8

Figure 5: Screenshot of NeatWork's Design Parameter Input Section That Shows Required Inputs and Default Values

NeatWork uses the service quality input (Figure 5) to determine the flow through each pipe segment during design. The higher the service quality, the greater the flows through each branch will be resulting in a more reliable, but more expensive system. The service quality is based on conditional and cumulative probabilities of how many faucets will receive water through that pipe segment. φ (L/s) represents the flow through the pipe needed for one faucet to have sufficient water. For each additional faucet added, φ is multiplied by the number of faucets to determine the flow through the pipe if that number of faucets were open. If the pipe leads to one faucet, the flow through that pipe will be φ L/s. If a pipe leads to six faucets, the flow will be between φ and 6φ depending on the number of faucets open. Because at least one faucet needs to be opened for a flow to exist through the pipe, the conditional probabilities can be calculated as follows (Agua Para La Vida, 2010):

$$\mathrm{P(B,A)} = \frac{r^{n} * (1-r)^{N-1} * \frac{\mathrm{N!}}{n! * (N-n)!}}{1-(1-r)^{N}} \tag{10}$$

In Equation 10,

r = probability that a faucet is open (defined as fraction of open faucets in NeatWork input)

N = total number of faucets

n = number of faucets open for trial

Using Equation 10, the flows and conditional and cumulative probabilities for the different combinations of open and closed faucets can be calculated for each pipe segment. An example of these probabilities for a pipe that leads to six faucets are presented in Table 9.

The service quality is equivalent to the cumulative probability. If the user selects a service quality of 0.5220, the system will design the pipes based on a flow of 2φ (the flow required to provide 2 taps with water) and that will be great enough to cover the demand flow 52.20% of the time. When the service quality falls between the cumulative probabilities for the flows, the flow is linearly interpolated and this becomes the suggested load factor. The user has the ability to enter modified load factors for each pipe segment.

Table 9: Flows and Probabilities Used in the Calculation of the Service Quality Factor in NeatWork

Open Faucets	1	2	3	4	5	6
Flow (L/s)	Φ	2φ	3φ	4φ	5φ	6φ
Conditional Probability	0.1958	0.3263	0.2900	0.1450	0.0387	0.0043
Cumulative Probability	0.1958	0.5220	0.8120	0.9570	0.9957	1

Another unique aspect of NeatWork is that it designs under the assumption that the consumers need practically no water pressure at the faucets. While pressure may not be needed, it minimizes the factor of safety that may be required due to errors in survey data. However, NeatWork does incorporate a factor of safety in the way it calculates the roughness factor of the pipes. Over time calcium deposits builds up in pipes in some locations of the distribution system and sediments in a PVC pipe of a gravity flow water system can result in higher frictional losses. NeatWork incorporates this into its calculations and uses a friction factor 4.5% greater than that of a smooth PVC pipe (Agua Para La Vida, 2010).

Along with using pipe sizes to obtain the desired headloss at each faucet, NeatWork also relies on flow reducers. The headloss through an orifice depends on the Reynolds number if the hole diameter exceeds 30% of the pipe diameter. The sizes of perforations used by NeatWork are almost always smaller than this. Therefore, the program calculates headloss based solely on flow rate and hole diameter as follows (Agua Para La Vida, 2010):

$$h_L = -\theta^4 \frac{Q^2}{d^4} \tag{11}$$

In Equation 11,

h_L = *headloss through the orifice (m)*

Θ = *orifice coefficient (unitless)*

Q = *flow through the orifice (m^3/s)*

d = *diameter of hole in orifice (m)*

While the orifice coefficient (Θ) can be changed by the designer, NeatWork uses a default value of 0.59. Since the manual was written more tests have been conducted suggesting that a better estimate for Θ is 0.62 (personal communication with Guillermo Corcos, 2015). This produces headloss values 35% smaller than Equation 5. The varying headloss for the target flow of 0.2 L/s is presented in Table 10.

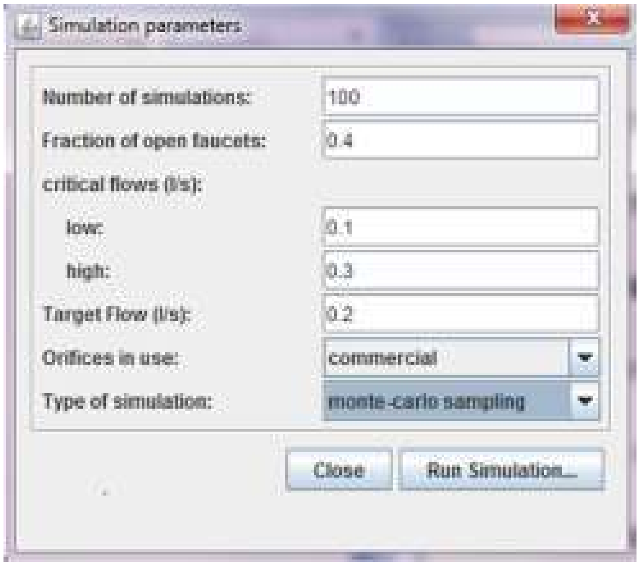
Table 10: Comparing Headloss Values through Orifices

Diameter (m)	NeatWork Formula (m)	Equation 5 (m)
0.003	73.0	113.3
0.004	23.1	35.9
0.005	9.5	14.7
0.006	4.6	7.1

Guillermo Corcos, the technical director for Agua Para la Vida, has performed a variety of tests systematically varying pressure loss, flows, and orifice diameter in order to test the NeatWork formula (Equation 11) and determined that the simplified NeatWork formula was acceptable to use for gravity flow aqueducts. Because the NeatWork formula was derived specifically for this application while Equation 5 is applied when using orifices to measure flows, this thesis proceeds using the NeatWork formula.

2.2.2 Simulation Phase

The simulation phase allows the designer to test the designs created by NeatWork or existing aqueduct designs that were constructed in the past. To start a simulation, the user can define variables in a pop-up window as shown in Figure 6. The values shown in Figure 6 are the default values provided by NeatWork.



Number of simulations: 100
Fraction of open faucets: 0.4
critical flows (l/s):
low: 0.1
high: 0.3
Target Flow (l/s): 0.2
Orifices in use: commercial
Type of simulation: monte-carlo sampling

Figure 6: Screenshot of Simulation Parameter Inputs in NeatWork

The NeatWork simulation will produce various results including the velocities through pipes, the node pressures, and a variety of information regarding the flow at faucets including: 1) faucet ID, 2) number of occurrences, 3) minimum flow 4) average flow, 5) maximum flow, 6) variability, 7) percentage below the lower bound, 8) percentage above the upper bound, and 9) number of failures. The user can then manipulate pipe sizes and change flow reducer sizes to improve the functionality of the system until the user believes that the level of service will meet the community needs.

NeatWork assumes that the storage tank will also have plenty of water. If the tank empties at some points during the day, the taps will have water less frequently than predicted by the NeatWork model. Measurements of dry season flows and calculations of water needs should therefore be performed to verify that there is sufficient water. This is essential for the sustainability of an aqueduct. For the purpose of this thesis, the author assumes there is always a sufficient amount of water in the storage tank so that the NeatWork analyses are accurate.

Chapter 3: Materials and Methods

3.1 Making a Water Level

Water levels are basic tools used to measure the change in elevations along an aqueduct. They can be made using two ½-inch PVC pipes or straight narrow sticks cut to be about 6-ft tall (the author's was 80-inches in length) and ¼-inch vinyl tubing about 32-ft long as seen in Figure 7.

Figure 7: A Completed Water Level

Using a tape measure and a permanent marker, the pipes are marked every inch or centimeter. The author used a water level marked in inches and converted the data to centimeters to use in NeatWork. For future water levels, it is recommended to mark everything in centimeters to eliminate this conversion. Using zip ties or duct tape, the tubing is attached about 5-inches from the bottom of the PVC pipes so that when the vinyl tubing is fully extended the pipes are 20-ft or 6-m apart. The tubing is continually attached to the top of the PVC pipes making sure not to cover any of the numbers. The tubing should be securely attached to the PVC pipes without pinching the tube preventing water from passing. The vinyl tubing is then filled with water so that the water reaches halfway up the PVC pipes. It is important to make sure all air bubbles are removed. This can be accomplished by raising the elevation of the tube close to the air bubble and gently tapping below the bubble.

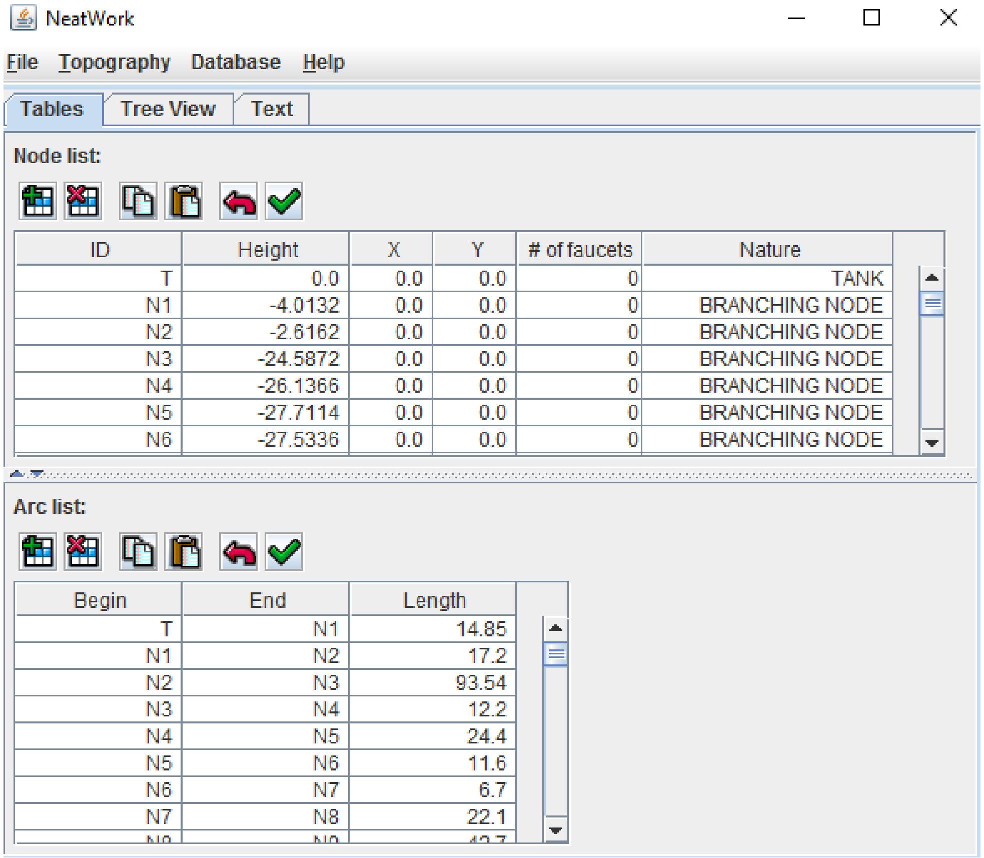
3.2 Data Collection and Organization

During the time the author served as a Peace Corps Volunteer, she surveyed the existing aqueduct in need of a new distribution network with the help of community members using a water level made as described above. A team cleared the path of the pipes with machetes so the author and her team of two helpers could survey.

Starting at the source and following the pipe, the author surveyed the entire system including all main lines and the individual branches leading to each house. While some houses have multiple faucets, the author only surveyed to the faucet used the most. The helpers would extend the water level to its maximum distance and would read off the closest number to the level of the water, which the author would record. The leading person would mark the spot of the water level so the follower could put their tube in the same spot and the process would be repeated. At crucial spots such as tees, changes in pipe sizes, and high and low points, the lead person would place his pipe at the crucial spot and the distance between the two pipes would be measured. GPS coordinates were also taken at all the crucial points. If the slope was too steep where the change in elevation was greater than what could be measured by the water level, readings would be recorded for two points closer together and their horizontal distance would be measured. After the existing aqueduct was surveyed, the additional houses that wanted to be added to the system were surveyed as well from the closest known point of the existing aqueduct.

Figure 8: Pictures from when the Author Surveyed in the Field

Once all the data was collected, the author used Microsoft Excel™ to organize the data into the proper formatting to use with the NeatWork program. A screenshot of the NeatWork Input screen is shown in Figure 9.



Node list:

ID	Height	X	Y	# of faucets	Nature
T	0.0	0.0	0.0	0	TANK
N1	-4.0132	0.0	0.0	0	BRANCHING NODE
N2	-2.6162	0.0	0.0	0	BRANCHING NODE
N3	-24.5872	0.0	0.0	0	BRANCHING NODE
N4	-26.1366	0.0	0.0	0	BRANCHING NODE
N5	-27.7114	0.0	0.0	0	BRANCHING NODE
N6	-27.5336	0.0	0.0	0	BRANCHING NODE

Arc list:

Begin	End	Length
T	N1	14.85
N1	N2	17.2
N2	N3	93.54
N3	N4	12.2
N4	N5	24.4
N5	N6	11.6
N6	N7	6.7
N7	N8	22.1

Figure 9: Screenshot of NeatWork Input Tables to Create a New Topography

NeatWork performs faster with fewer data points so the author simplified the data to include only critical points including the tank, high points, low points, tees, and faucets to use as nodes. She calculated the relative altitude for each node, setting the tank as the benchmark at an elevation of 0-m. She also calculated the distance between each node. NeatWork has additional columns that allow the user to enter horizontal coordinates that may be helpful when designing loop systems. However, NeatWork itself does not use these coordinates during the design (Agua Para La Vida, 2010). Using the coordinate features provided no advantages since the Santa Cruz system contains no loops. Therefore, 0 was inputted for the X and Y coordinates. The tank and all branching nodes have 0 faucets while all houses were assumed to have 1 faucet to simplify the aqueduct design. The following numbers were assigned for the nature of each node: tank-0, branching node-1, and faucet-2. The author modified the Excel document and copied and pasted the tables into Neatwork to create the various topography files she needed to perform the analysis of the aqueduct.

3.3 Procedure for Analyzing Sample Aqueduct

The author utilizes NeatWork as the primary tool for analyzing the system. For the purpose of this research she used its default values for running simulations. She also assumed that a water committee is trained on how to repair leaks in the system and will repair them on a regular basis so friction losses associated with broken pipes can be ignored during the analysis.

As explained in Section 1.7, the aqueduct used for this research has 60 confirmed connections and 13 potential connections. All 73 connections were surveyed for this study allowing them to be analyzed using the NeatWork software. In order to better analyze how the addition of these 13 houses would affect performance of the aqueduct a variety of different simulations were run in NeatWork.

The designs come from two topographies; “All” which includes all 73 houses and “As Is” which only contains the 60 confirmed connections. The Excel tables copied into NeatWork are reproduced in Appendix B. From both of the topography files, NeatWork produced designs utilizing only the pipes and flow reducers as presented in Table 11.

Table 11: Design Input Criteria for Design of Sample Aqueduct

Pipe Size		**Flow Reducer Diameter**	
Nominal Diameter (in)	**Standard Dimension Ratio (SDR)**	**(m)**	**(in)**
0.5	13.5	0.002381	3/32
1	26.0	0.003175	1/8
1.5	26.0	0.003969	5/32
2	26.0	0.004763	3/16
3	26.0	0.005556	7/32
		0.006350	1/4

These pipe sizes were selected based on local availability, necessary strength, and cost. The pipe sizes listed in Table 11 are also available in Standard Dimension Ratio (SDR) 41, but these are not recommended for use in gravity flow water systems because of their low pressure ratings. In some stores in Penenomé, the city closest to Santa Cruz with hardware stores, 2.5-inch PVC pipe could be specially purchased making it more expensive. Other stores also carried 1.25-inch PVC, but at almost the same price as the 1.5-inch pipe. Therefore, the 1.25-inch and 2.5-inch pipes were left out of the design. This also reduces the number of extra pipes a water committee needs to have locally available to repair damaged pipes.

The holes for the flow reducers are created using hand drills which were only available in Panama in inches. Therefore, the standard drill bit sizes in inches were converted to meters, the unit used in NeatWork, so that the edited orifice database in NeatWork reflects the available sizes.

Occasionally, the NeatWork design provided a 1-inch pipe leading directly to a tapstand which makes it more difficult in the field to connect the tapstand and install the flow reducer.

Therefore, the author modified the design in Neatwork to include 6-m (the standard pipe length) of ½-inch PVC pipe before every faucet where this occurred. The designs were then saved as "All" and "As Is" in Neatwork. A simulation was run on both of the designs using the NeatWork values. Both designs were compared to each other noting the pipe sections and flow reducer diameters that changed from the addition of the 13 unconfirmed houses.

If the 13 unconfirmed houses represent houses being added to the system in the future, it is more likely that they were not included in the original design. Therefore, another design file was created in NeatWork using the "All Topography"; however, pipe size constraints were input to match the pipe sizes from the "As Is" design file pipe sizes. After NeatWork provides an initial design, the flow reducer sizes must be manually changed to match those from the "As Is" design file for the existing houses because a limitation of NeatWork is that is does not allow the designer to specify the size of flow reducers prior to a design. This design was saved as "All As Is Sizes" and a simulation using the default values was run on this design. This file represents the correct flow reducer sizes according to NeatWork.

However, without the use of NeatWork, most communities will not be able to install the appropriate sized flow reducer. Therefore, the flow reducer sizes were modified in the "All As Is Sizes" design to reflect different scenarios and saved as different design files: if no flow reducers are installed- "All As Is Sizes No Discs, if the most common flow reducer size of 5/32-inch is installed for all new houses- "All As Is Sizes Discs 396," and if the flow reducer is sized based on the flow reducer size of the closest house- "All As Is Discs Closest." The flow reducer sizes used when sized based on the closest house are provided in Table 12.

The descriptions from the preceding six design files are summarized in Table 13. The results from the different NeatWork simulation were compared to evaluate the differences in service quality between the designs.

Table 12: Flow Reducer Sizes for Design File Based on Flow Reducers Size of the Closest House

New House	Closest House	Flow Reducer Size (in)
N1	1	5/32
N2	19	5/32
N3	20	5/32
N4	25	7/32
N5	37	5/32
N6	45	None
N7	49	1/8
N8	49	1/8
N9	52	3/16
N10	52	3/16
N11	58	5/32
N12	60	None
N13	60	None

Table 13: Summary of NeatWork Design Files Used to Analyze the Santa Cruz Aqueduct

Design File Name	Modified or Created from	Description of Design
All	All Topography File	The NeatWork design for all 73 potential connections.
As Is	As Is Topography File	The NeatWork design for the 60 confirmed connections.
All As Is Sizes	All Topography File	The design for all 73 potential connections with pipe sizes manually restricted to those of the confirmed design sizes. After the NeatWork design, the author manually changed the flow reducer sizes to match the confirmed design.
All As Is Sizes No Discs	All As Is Sizes Design File	The flow reducer sizes were modified so that none of the 13 new connections had flow reducers installed.

Table 13: (Continued)

All As Is Sizes Discs 396	All As Is Sizes Design file	The flow reducer sizes were modified so that all 13 of the new connections would have a flow reducer sized at 5/32-inch.
All As Is Sizes Discs Closest	All As Is Sizes Design File	The flow reducer sizes were modified so that the 13 new connections have a flow reducer equal to that of the closest confirmed house on the system.

Along with the NeatWork analysis of varying designs, the author examined the system looking for patterns and ways to simply flow reducer sizes in order to create a tool appropriate for local water committees. This procedure was more experimental where the author based her procedures on her findings as she went.

First, the different flow reducer sizes, relative altitudes, and total distances from the tank for each faucet were compared. These values come from the original surveying data. Next, the author determined different pressures at each node based on the “All As Is Sizes”. NeatWork provided an average pressure and a maximum pressure that occurred at each node during the simulation. Available head was calculated using traditional fluid mechanics as well. Using the average flow between each node provided by the NeatWork simulation, the author used Equation 2 to calculate a friction factor and Equation 1 to calculate a headloss for each segment of pipe. A cumulative headloss leading to each node was summed and converted to available head by subtracting the total headloss form the distance in elevation between the tank and the node. Appendix E shows the spreadsheet used to calculate the available head. The ranges for average pressure, maximum pressure, and available head were determined for each flow reducer size.

Next, the author examined how the size of the flow reducer determined by NeatWork in the “All As Is Design” compared to the flow reducer size installed in the closest house and noted the locations where they differed. To better understand these locations, the author created profiles of these from her surveying data. She then identified other areas of the aqueduct that did not have new houses that would have similar profiles and plotted these as well. The author summarized the trends in three different rules that could be used to size flow reducers without the use of NeatWork.

3.4 Testing Rules from Analysis

In order to test the rules made from the analysis explained in detail in Section 4.1, the author added experimental houses where additional houses may be built in the future. Since the actual aqueduct that was built for the community of Santa Cruz was designed from the Neatwork design for all the houses, the "All" design file was used as the basis for sizing the flow reducers of the experiment houses. The author selected 9 locations that are shown in Figure 10.

Initially, the author created a new topography file called "Experiments" that included all 9 of the experiment houses. Using this file and inputting the sizes of the pipes from the "All" design file, a new design was created entitled "Experiments All Sizes." However, because NeatWork does not allow the user to input flow reducer sizes before the design, it changed the flow reducer sizes on 25 houses including most of them on the branches that had experiment houses added to it. This is drastically different from when this same technique was performed to create the "All As Is Sizes" design that only resulted in a change of three flow reducer sizes. This difference is believed to be a result from the fact that in the "Experiments" topography all the additional houses were placed at the end of the branches when in the "All" topography the new houses were spread randomly throughout the system. With the large number of changes in flow reducers, the sizes given to the new houses do not accurately represent the sizes that those houses should have if it was individually added to the aqueduct.

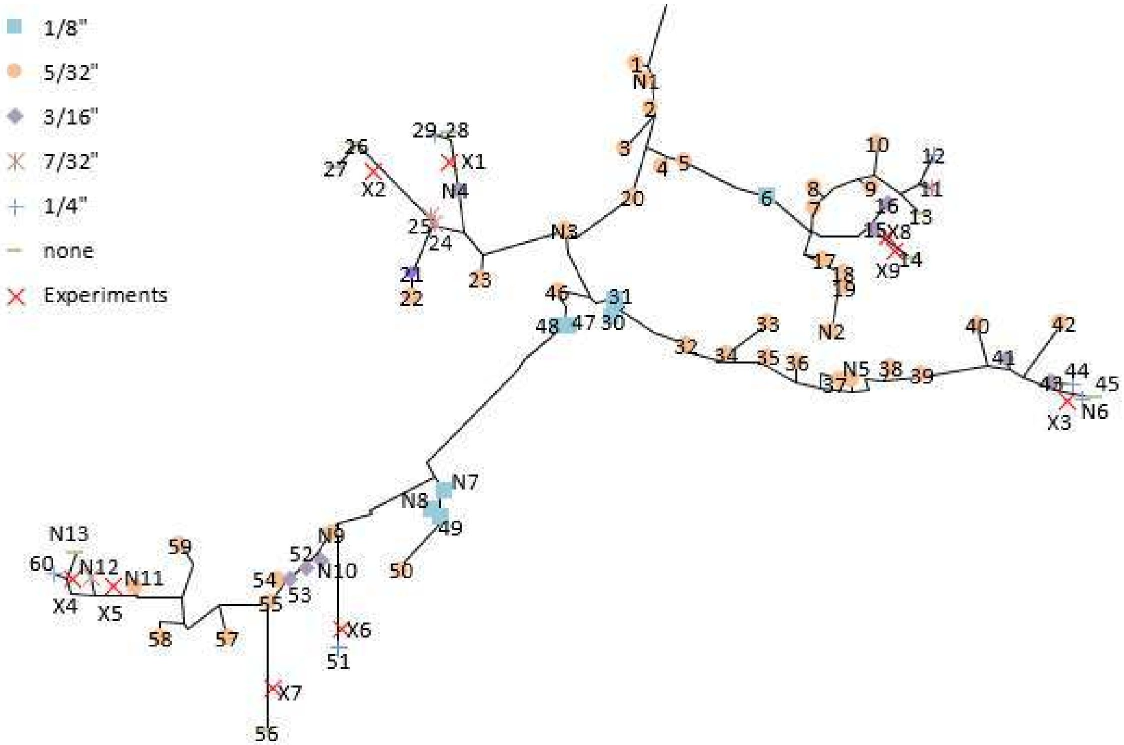


Figure 10: Map Including Experiment Houses to Test Developed Rules for Sizing Flow Reducers Showing Flow Reducer Sizes and Faucet Numbers from "All" Design (not to scale)

To fix this problem and get more accurate flow reducer sizes, nine new topography files were created named "X1" to "X9" where each one only had the addition of one experimental house. Design files, "X1 All Sizes" - "X9 All Sizes", were then created using these nine topographies and manually inputting the pipe sizes from the "All" design file. While the majority of the flow reducer sizes stayed the same, in many of the trials, the flow reducer sizes of nearby houses changed. The NeatWork sized flow reducer still may not necessarily represent the ideal size for the new house because the end branches are sensitive to new houses and some flow reducer sizes changed. While changing the flow reducers in other surrounding houses might create a more optimal aqueduct, this would be more complicated for the water committee. Therefore, this thesis assumes that all existing flow reducers will remain the same size and were changed to match the initial size from the "All" design file. If the NeatWork sized flow reducer varied from the flow reducer size predicted from the author's conclusions, the flow reducer for the new experimental house was changed and saved as a new design file, such as “X1 All Sizes PS” where PS stands for predicted size. For further comparison, additional design files were made to test how the system would operate if the flow reducer was installed to match that of the closest house. The flow reducers for the new experiment houses were changed and saved with a “CH” at the end of the file name for closest house. The author ran NeatWork simulations on all of these design files to determine which flow reducer sizes optimized aqueduct performance.

Chapter 4: Results and Discussion

4.1 Analysis of Sample Aqueduct

The results of the simulations on the various designs were analyzed. When NeatWork created designs, the majority of the pipe sizes and flow reducers were the same. However, there were some differences in estimated pipe size. The complete distribution system for the “All” design file for 73 houses consists of 4,284-m of pipe. 650-m of this total pipe length increased in diameter when the design included the entire system of 73 houses compared to only the 60 confirmed houses. This means that 13.5% of the pipe diameter dimensioning should be changed when the number of system users is increased from 60 to 73 (22%). This is because as more houses are added to the system the flow through the pipes becomes larger to meet increased demand of the community. As flows increase, headloss through the pipe also increases, which makes it more difficult for the water to arrive at the higher elevation homes and those homes farther from the storage tank. To prevent additional headloss, larger diameter pipes can be added as the bigger pipes create less headloss. The specific places where the pipe sizes are different identified from NeatWork simulations are presented in Table 14 and the summary of the lengths of pipe sizes that would require changing under this scenario is provided in Table 15.

While 13.5% of the pipes increased in diameter when the 13 additional houses were added, only 3 of 60 (5%) of the confirmed houses required a change in flow reducer size. The differences in flow reducer sizes are shown in Table 16 and their locations in the aqueduct are presented in Figure 11.

Table 14: Differences in Determined Pipe Sizes from NeatWork between "As Is" Design and "All" Design

		As Is		All	
Start Node in NeatWork	End Node in Neatwork	Length of Pipe (m)	Nominal Pipe Size (in)	Distance (m)	Nominal Pipe Size (in)
N10	N11	54 46.76	1.5 1	78 22.76	1.5 1
N28	N29	42.85	2	42.85	3
N29	N30	4.5	2	4.5	3
N39	N40	73.24 30	1 0.5	90 13.24	1 0.5
N41	N42	17.2 15.5	1 0.5	36 6.7	1 0.5
N43	N44	18.3	2	18.3	3
N44	N45	16.08	2	16.08	3
N45	N46	37.2	2	15.4 21.8	3 2
N46	N47	30.5	1.5	30.5	2
N47	N48	40	1.5	40	2
N48	N49	50	1.5	50	2
N49	N50	4.2	1.5	4.2	2
N50	N51	139	1.5	139	2
N51	N52	21.35	1.5	21.35	2
N67	N68	28.79 13.91	1.5 1	42.7	1.5
N68	N69	46.79	1	46.79	1.5
N90	N91	22.68 13	1 0.5	35.68	1
N91	N92	20	0.5	20	1
N92	N93	47.97	0.5	47.97	1
N93	N94	37.87	0.5	31.87 6	1 0.5
N94	N95	6	0.5	6	1

Table 15: Total Length of Pipes Changed between "As Is" Design and "All" Design

Pipe Size Change (in)	Length of Pipe Requiring Change (m)
2 to 3	97
1.5 to 2	285
1 to 1.5	114
0.5 to 1	154

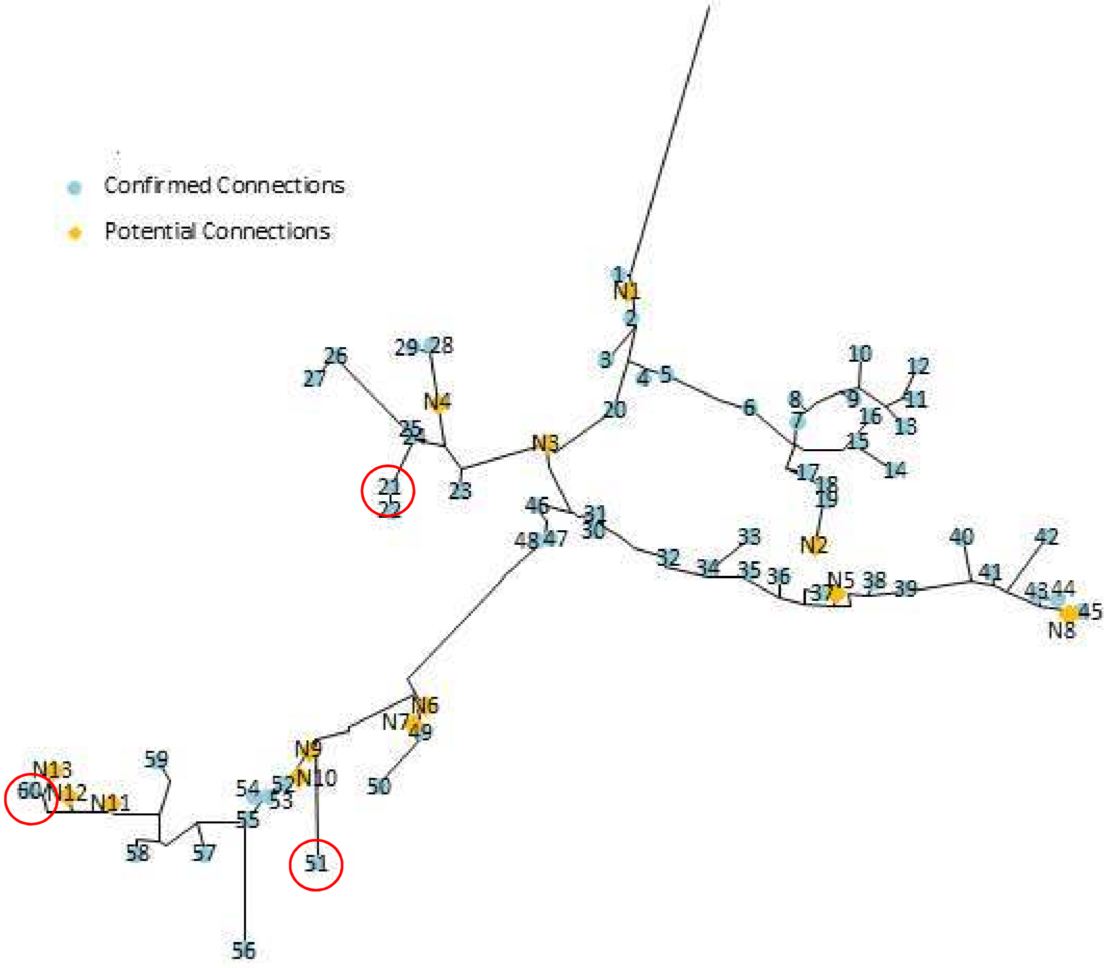


Figure 11: Location of Faucets as Indicated in the Red Circles where the Flow Reducer Size Changes when the Design Changes from the "As Is" Design to the "All" Design (not to scale)

Table 16: Differences in Flow Reducer Sizes between “As Is” Design and “All” Design

	Flow Reducer Size (in)	
House	From “As Is” Design	From “All” Design
21	0.003969	0.004763
51	--	0.006350
60	--	0.006350

NeatWork simulations performed with the default values listed in Figure 6 were run on the six designs summarized in Table 13. Appendix C presents the complete design results including number of occurrences that a faucet was used in a simulation, minimum flow, average flow, maximum flow, variability of flows, percentage of time flow is less than 0.1 L/s, and percentage of times flow is greater than 0.3 L/s. While the flows changed in all the connections, a notable change is defined as if in one of the simulations a new no flow (0.0 L/s minimum flow) or that the flow is below 0.1 L/s more than 25% of the time. The notable changes in flows between the designs are summarized in Table 17.

Table 17: Notable Changes between Designs for Sample Aqueduct in Minimum Flow and Percentage of Time Below 0.1 L/s

	As Is		All		All As Is Sizes		All As Is Sizes No Discs		All As Is Sizes Discs 396		All As Is Sizes Discs Closest	
House	min (L/s)	<0.1 L/s (%)	min (L/s)	<0.1 L/s (%)	min (L/s)	<0.1 L/s (%)	min (L/s)	<0.1 L/s (%)	min (L/s)	<0.1 L/s (%)	min (L/s)	<0.1 L/s (%)
13	0.000	11.9	0.072	2.6	0.042	5.7	0.000	12.1	0.041	11.1	0.032	13.6
14	0.000	9.4	0.082	2.7	0.047	10.3	0.000	16.7	0.000	8.5	0.043	9.3
26	0.064	6.3	0.056	12.2	0.016	15.0	0.000	23.7	0.025	12.2	0.000	16.2
44	0.082	2.7	0.121	0.0	0.016	7.1	0.000	9.5	0.068	12.8	0.000	23.3
45	0.000	20.5	0.000	4.8	0.000	43.8	0.000	41.2	0.000	73.5	0.000	53.3
51	0.132	0.0	0.134	0.0	0.000	29.0	0.000	82.1	0.000	97.5	0.000	30.0
56	0.000	13.6	0.054	2.5	0.000	55.3	0.000	91.3	0.000	52.4	0.000	60.0
60	0.124	0.0	0.087	10.3	0.000	57.6	0.000	88.6	0.000	55.0	0.000	60.5
N6	--	--	0.142	0.0	0.064	2.5	0.076	2.9	0.049	33.3	0.000	2.2
N12	--	--	0.140	0.0	0.052	31.6	0.000	51.1	0.047	74.3	0.041	14.3
N13	--	--	0.108	0.0	0.015	61.1	0.000	84.2	0.010	53.7	0.000	63.4

Also, when flow reducers are not added or are undersized, the new connections can have flows greater than 0.3 L/s. This occurred in eight of the 13 connections when no flow reducers were added (All As Is Sizes No Discs) and are presented in Table 18.

Table 18: Connections with Greater than 0.3 L/s when Flow Reducers are Not Installed

New House	Max (L/s)	> 0.3 L/s (%)
N1	0.3374	100
N2	0.4438	92
N3	0.7127	100
N4	0.4532	100
N5	0.5017	100
N7	0.7107	100
N8	0.6085	100
N11	0.4693	87

This creates inequalities between the houses because some will have large flows all the time while others will experience low or no flows. In many communities there are no water meters so households pay a rate per household or family instead of by quantity of water consumed. Thus, users view it as unfair if some houses have access to more water than others. Large flows also put more wear and tear on the faucets leading to a shorter life span and making leaky faucets more likely. Faucets with large flows also waste more water if accidentally left on.

This analysis confirms the importance of continually installing flow reducers as the water supply system expands. Without the flow reducers, a large inequality of flows was found to exist where one house may have 0.7 L/s while another has no flow. Without installation of flow reducers in the new houses, service quality decreases shown by the fact that nine houses were found to have no flow at certain times.

Although, the best solution is designing for the expanded system from the beginning, unfortunately this is not always feasible. It may be possible, to systematically include larger pipe diameters throughout the system to account for additional houses. However, this topic is beyond the scope of this thesis. Instead, due to the minimal changes in the design (13.5% of pipe sizes and three flow reducers), the author proceeded as if the design was made only for the confirmed houses and that houses were gradually added to the system in the development of the thesis's decision support tool. This does not match how the design was implemented, but rather is a more realistic approach to how Peace Corps Volunteers will design the system in the field without knowing where future houses will be placed.

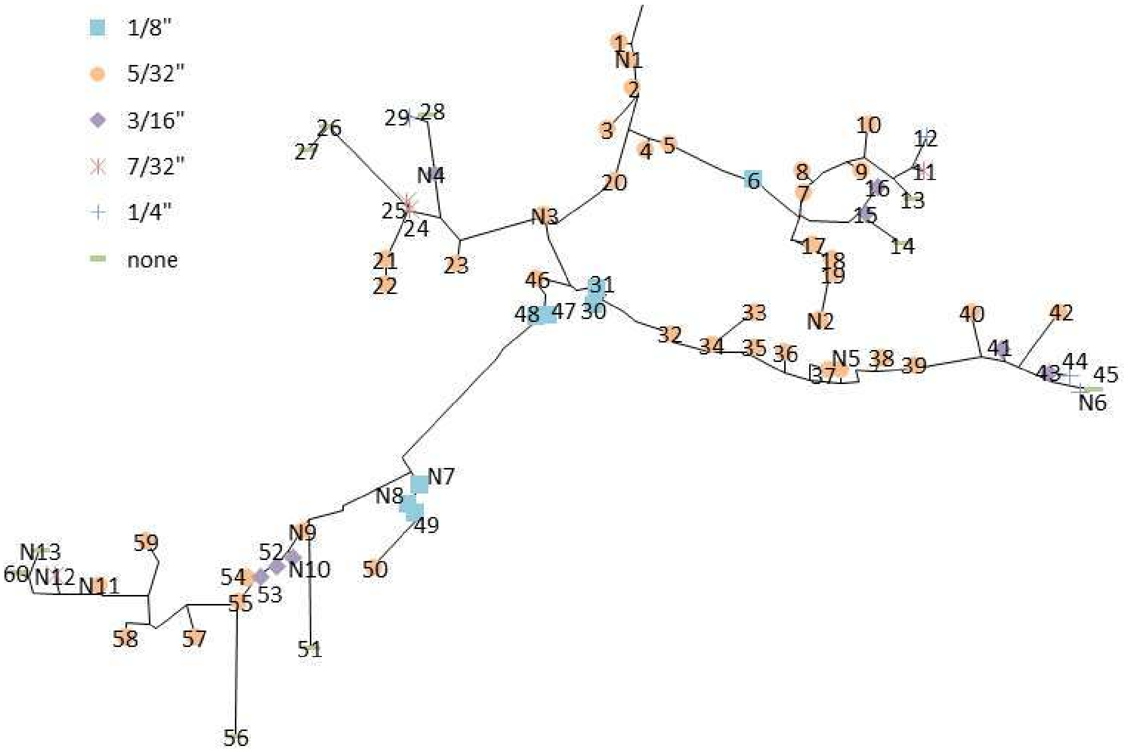


Figure 12: Map of Flow Reducer Sizes and Faucet Numbers from "All As Is Sizes" Design File (not to scale)

The results discussed above show that installing flow reducers, even if not ideally sized, produces better results for a community gravity flow water system than not installing them at all. However, the systems will have the highest service quality if the water committees can install the ideal flow reducer size even without the use of NeatWork. Accordingly, the author analyzed distance from tank, relative elevation, available head, and pressures at tapstands. The location and sizes of the flow reducers from the "All as is sizes" design file are presented in Figure 12.

This information is also presented in Table 19 with the relative altitude using the tank as the benchmark.

Table 19: Flow Reducer Sizes, Relative Altitudes, Length of Pipes between Tank and Faucet for Santa Cruz Aqueduct, Available Head, Average Pressure, and Maximum Pressure

House	Flow Reducer Size (in)	Relative Altitude (m)	Length of Pipes Between Tank and Faucet (m)		House	Flow Reducer Size (in)	Relative Altitude (m)	Length of Pipes Between Tank and Faucet (m)
1	5/32	-27.8	145		38	5/32	-22.4	840
2	5/32	-29.3	172		39	5/32	-35.3	842
3	5/32	-32.9	319		40	5/32	-36.8	960
4	5/32	-32.4	264		41	3/16	-33.7	946
5	5/32	-36.1	272		42	5/32	-39.0	1033
6	1/8	-46.4	383		43	3/16	-31.9	1004
7	5/32	-46.1	445		44	1/4	-25.2	1016
8	5/32	-43.9	468		*45*	none	-22.2	1091
9	5/32	-34.6	510		46	5/32	-47.4	468
10	5/32	-35.5	549		47	1/8	-48.3	501
11	7/32	-26.0	575		48	1/8	-48.4	501
12	1/4	-23.2	600		49	1/8	-49.3	763
13	none	-20.9	585		50	5/32	-40.5	839
14	none	-20.1	566		51	none	-17.1	879
15	3/16	-31.1	514		52	3/16	-25.4	884
16	3/16	-29.5	538		53	3/16	-26.5	900
17	5/32	-44.8	472		54	5/32	-31.3	917
18	5/32	-45.9	505		55	5/32	-30.8	935
19	5/32	-46.0	502		56	none	-15.5	1092
20	5/32	-27.9	249		57	5/32	-36.4	1053
21	5/32	-31.4	552		58	5/32	-42.2	1115
22	5/32	-35.5	585		59	5/32	-44.2	1137
23	5/32	-29.9	487		60	none	-27.5	1233
24	3/16	-22.4	520		N1	5/32	-29.8	151
25	7/32	-23.1	557		N2	5/32	-47.7	542
26	none	-17.3	629		N3	5/32	-35.9	316
27	none	-19.1	664		N4	3/16	-23.8	535
28	none	-18.0	612		N5	5/32	-30.2	785
29	1/4	-19.8	590		N6	1/4	-25.6	1075
30	1/8	-48.3	460		N7	1/8	-50.1	727
31	1/8	-48.6	455		N8	1/8	-49.8	757
32	5/32	-41.0	556		N9	5/32	-33.8	831

Table 19: (Continued)

33	5/32	-38.6	672		N10	3/16	-24.7	865
34	5/32	-36.7	620		N11	5/32	-40.4	1124
35	5/32	-34.6	656		N12	7/32	-28.9	1198
36	5/32	-34.2	724		N13	none	-27.6	1257
37	5/32	-30.2	758					

Table 19 shows that using only elevation and direct distance from the storage tank does not provide sufficient information to size a flow reducer. This is because it does not account for pipe size and flow through the pipes which affect the headloss. Therefore, the remaining head available at each house was calculated. This head would be available at the faucet without a flow reducer. The simulation phase also provides average node pressure and maximum node pressure at each faucet during all the simulations assuming the given flow reducer size is installed. This information is presented along with flow reducer size in Table 20.

Table 20: Calculated Available Head, Average Pressure from NeatWork Simulation, and Maximum Pressure from NeatWork Simulation for Each Faucet

House	Flow Reducer Size (in)	Calculated Available Head (m)	Average Pressure (m)	Maximum Pressure (m)
1	5/32	25.1	15.6	27.8
N1	5/32	27.3	19.1	29.8
2	5/32	26.7	17.6	29.3
3	5/32	23.4	18.4	32.9
4	5/32	28.1	17.5	32.4
5	5/32	32.4	22.0	36.1
6	1/8	37.6	25.0	46.4
7	5/32	32.9	31.4	46.1
8	5/32	30.1	24.2	43.9
9	5/32	20.7	22.1	34.6
10	5/32	20.7	21.3	35.5
11	7/32	11.5	15.6	26.0
12	1/4	7.7	14.6	23.2
13	none	11.9	13.6	20.9
14	none	5.4	14.3	20.1
15	3/16	18.3	16.8	31.1
16	3/16	15.4	18.3	29.5
17	5/32	29.0	30.0	44.8

Table 20: (Continued)

18	5/32	28.5	31.7	45.9
19	5/32	28.7	26.2	46.0
N2	5/32	28.6	33.9	47.7
20	5/32	25.0	15.9	27.9
N3	5/32	31.8	20.1	35.9
21	5/32	19.5	19.1	31.4
22	5/32	22.2	21.7	35.5
23	5/32	19.1	17.0	29.9
24	3/16	11.2	13.4	22.4
25	7/32	10.4	14.5	23.1
26	none	5.4	10.4	17.3
27	none	5.7	11.2	19.1
N4	3/16	12.9	14.3	23.8
28	none	5.1	11.0	18.0
29	1/4	7.7	12.9	19.8
30	1/8	40.0	30.0	48.3
31	1/8	40.9	28.7	48.6
32	5/32	31.5	23.8	41.0
33	5/32	25.1	24.7	38.6
34	5/32	26.2	23.9	36.7
35	5/32	23.2	20.8	34.6
36	5/32	21.7	20.2	34.2
37	5/32	17.4	16.6	30.2
N5	5/32	17.1	20.0	35.7
38	5/32	20.2	16.6	30.2
39	5/32	19.9	20.5	35.3
40	5/32	17.8	21.7	36.8
41	3/16	15.6	22.6	33.7
42	5/32	18.5	23.8	39.0
43	3/16	13.5	19.2	31.9
44	1/4	6.4	14.6	25.2
N6	1/4	7.2	15.4	25.6
45	none	3.9	11.5	22.2
46	5/32	29.5	26.1	47.5
47	1/8	39.6	23.7	48.3
48	1/8	39.6	31.0	48.4
N7	1/8	36.2	26.6	50.1
N8	1/8	34.5	25.4	49.8
49	1/8	33.8	28.6	49.3

Table 20: (Continued)

50	5/32	24.4	23.1	40.5
51	None	-3.1	10.6	17.1
N9	5/32	20.7	16.2	33.8
N10	3/16	5.4	13.6	24.7
52	3/16	12.1	16.5	25.4
53	3/16	7.4	15.4	26.5
54	5/32	17.7	18.5	31.3
55	5/32	11.6	17.3	30.8
56	none	6.6	8.2	15.5
57	5/32	14.4	19.6	36.4
58	5/32	18.8	26.2	42.2
59	5/32	25.8	22.5	44.2
N11	5/32	24.5	25.5	40.4
N12	7/32	12.4	17.9	28.9
N13	none	11.2	17.6	27.6
60	none	11.4	18.4	27.5

Table 20 shows there is not a perfect relationship between flow reducer size and available head or pressure. Each flow reducer has a range of available heads and pressures and these ranges overlap. The ranges of pressure for each flow reducer size are provided in Table 21.

Table 21: Ranges of Calculated Head, Average Pressure, and Maximum Pressure for Different Flow Reducer Sizes

Flow Reducer Size (in)	Calculated Head (m)	Average Pressure (m)	Maximum Pressure (m)
1/8	33.8-40.9	23.7-31.0	46.4-50.1
3/16	11.6-32.9	15.6-33.9	27.8-47.7
5/32	5.3-18.2	13.6-22.8	23.8-33.7
7/32	10.4-12.4	13.4-17.9	22.4-28.9
1/4	6.4-7.7	12.9-15.4	19.8-25.6
none	-3.1-11.9	8.2-18.4	15.5-27.6

It makes sense that the ranges for the pressure would overlap because the goal of a flow reducer is to equalize pressure between houses allowing for a more equal distribution of flow. The fact that the range of head losses varies as much as it does may seem surprising; however, the reason for this is because NeatWork is trying to ensure equality on individual branches as well as in the entire system. Therefore, available head alone cannot predict the size of a flow reducer. Available head would also be a difficult concept to explain to community members, making it unrealistic in a guide for water committees.

An easier option would be to size the flow reducer so that is the same size as the flow reducer of the house which is geographically closest to the new house. The new aqueduct with flow reducers installed based on that of the closest house was tested and the results are displayed in Table 17. However, the serviceability decreased more than necessary (an additional four houses experience no flows) because the flow reducers of the closest house and the ideal size determined with NeatWork are not always the same. How they compare for the Santa Cruz aqueduct was examined in this study and is presented in Table 22. The locations where the sizes differ are circled in Figure 13.

Table 22: Comparison of Flow Reducer Size Based on the Closest House and from the NeatWork Design

New House	Closest House	Disc Size of Closest House (in)	Ideal Disc Size determined by NeatWork (in)	Comparison of Disc Sizes
N1	1	5/32	5/32	Same
N2	19	5/32	5/32	Same
N3	20	5/32	5/32	Same
N4	25	7/32	3/16	Ideal Smaller
N5	37	5/32	5/32	Same
N6	45	None	1/4	Ideal Smaller
N7	49	1/8	1/8	Same
N8	49	1/8	1/8	Same
N9	52	3/16	5/32	Ideal Smaller
N10	52	3/16	3/16	Same
N11	58	5/32	5/32	Same
N12	60	None	7/32	Ideal Smaller
N13	60	none	none	Same

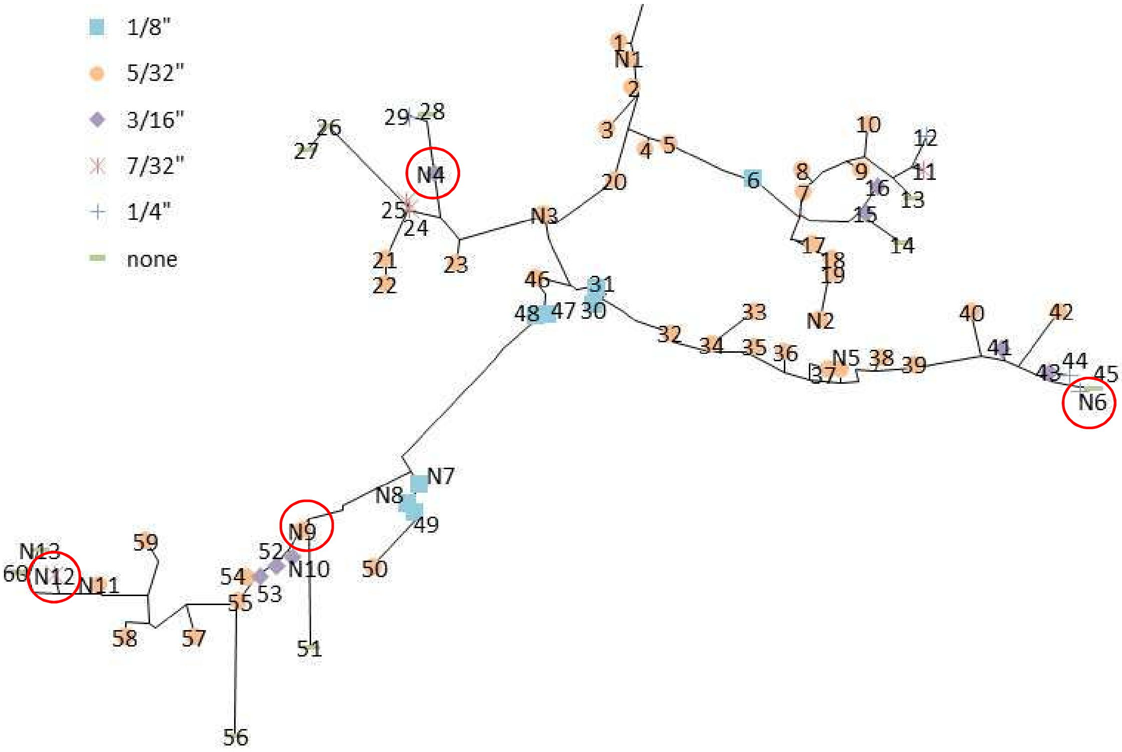


Figure 13: Map of Faucet Locations as Indicated in the Red Circles where Flow Reducer Size Changes from that of Closest House and Ideal Size from NeatWork Design (not to scale)

With the exception of house N9, the houses where the flow reducer of the closest house does not match the ideal size are all located towards the end of a branch of the system. These branches are also sloping upwards, so that the farthest house is higher on the hill as shown in the slopes leading up to house 29, 45, and 60. This is also reflected in the slopes leading to house 12 and 16. The house near the end of a branch requires a different flow reducer size with just a small change in elevation and distance from the closest house. The profiles of these sections of the aqueduct are displayed in Figures 14-17. While the profiles have different axis, the slopes are all the same.

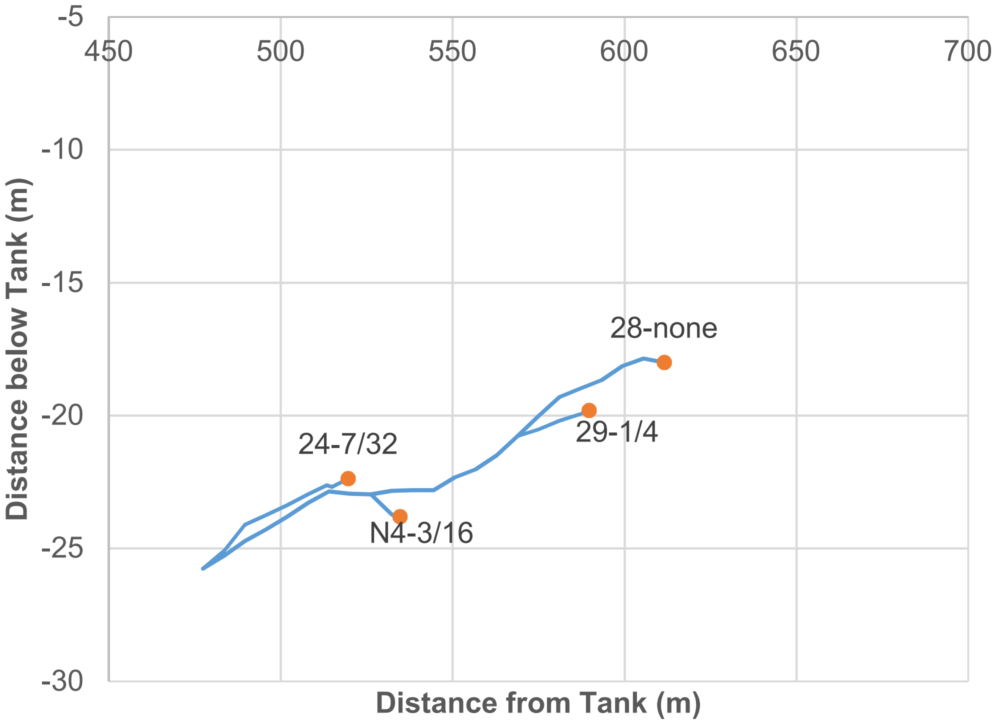


Figure 14: Profile of Aqueduct for Houses 24-29 with Flow Reducer Sizes Indicated (in inches)

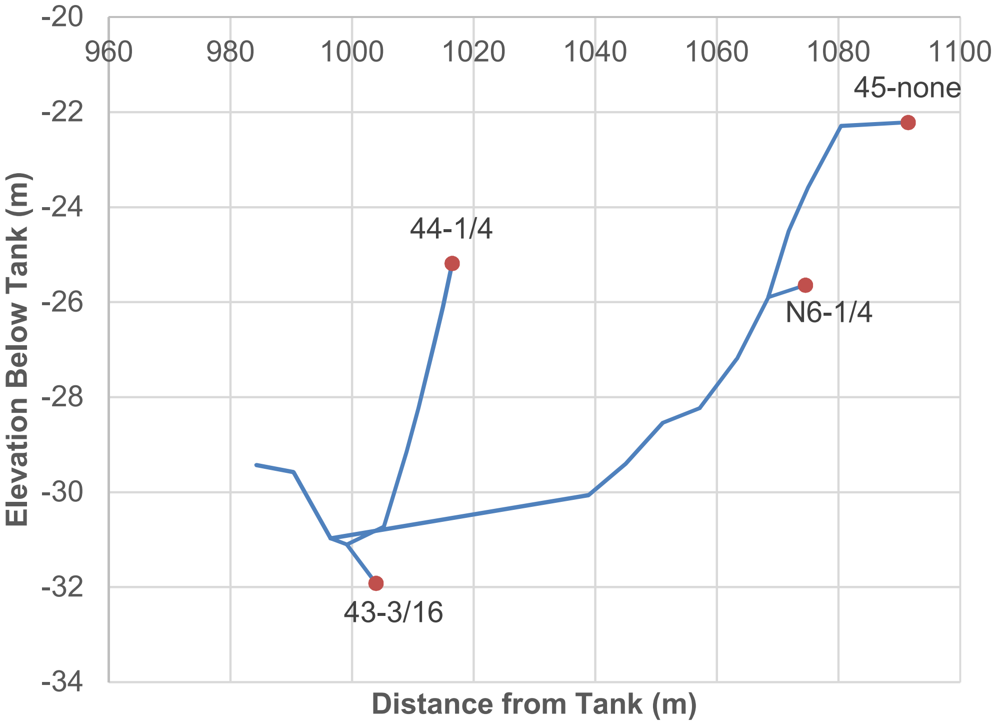


Figure 15: Profile of Aqueduct for Houses 43-45 with Flow Reducer Sizes Indicated (in inches)

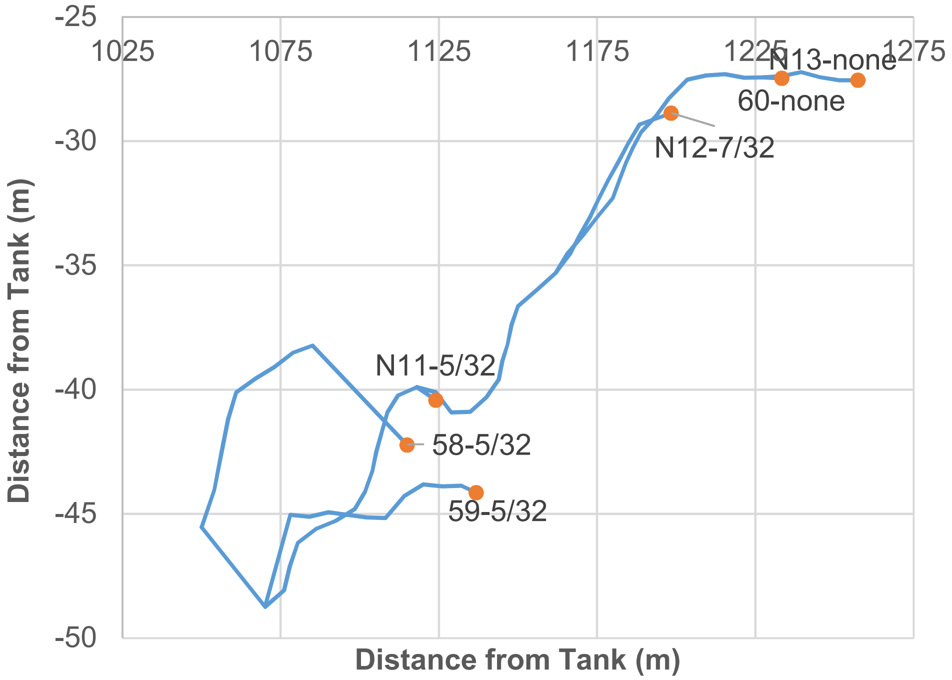


Figure 16: Profile of Aqueduct for Houses 58-60 with Flow Reducer Sizes Indicated (in inches)

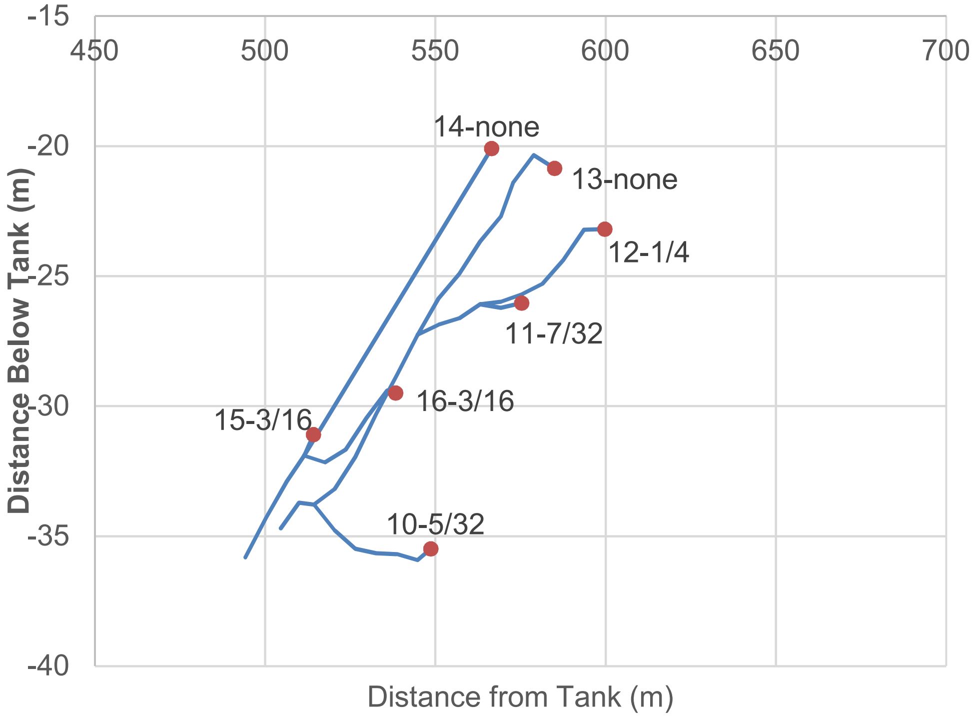


Figure 17: Profile of Aqueduct for Houses 10-16 with Flow Reducer Sizes Indicated (in inches)

The profiles for houses 10-13 and 14-16 are similar to the other profiles as they all are end branches that slope upwards. The individual branches also do not have all the flow reducer sizes represented. However, unlike the other end branches, these branches are geographically close together and between the two of them include all the flow reducer sizes, which may affect the new flow reducer sizes. Based on the preceding analysis, the following rules about sizing flow reducers for future houses were created (and tested later in this research to determine their validity):

1) Houses in the central area of the distribution system; i.e., a house surrounded by lots of houses and with multiple houses after it, will have the flow reducer of equivalent size to that of the closest house. For example, in Figure 13 the new house numbered as N7 has the same size flow reducer as its closest existing house, house 49.
2) Houses added on an end branch, i.e., the last section of a pipe where only a few houses remain and the topography slopes upward and all flow reducer sizes are not present, new houses should have the flow reducer size smaller than the house the comes after it. For example, in Figure 13, the new house numbered N6 has a flow reducer (1/4”) which is a size smaller than the house that comes after it, house 45 (no flow reducer).
3) Houses added on an end branch where consecutive flow reducer sizes are present in the region will have the size of the flow reducer based on the size of the house at the closest elevation. For example, in Figure 13, a house added between houses 14 and 15 at the same elevation as house 11, should have the same flow reducer size as house 11.

4.2 Analysis of Experiment Houses to Test Rules from Aqueduct Analysis

Rule 1 (that houses placed in the middle of the system will need the same size flow reducer that is installed in the closest house) did not need to be tested with experiment houses. New houses N1, N2, N3, and N5 as shown in Figure 12 supported this conclusion in the initial analysis. While house N9 did not support this conclusion, no notable changes in flows occurred when the ideal flow reducer size was changed for that of the closest house. Since this had many houses supporting this rule in the initial analysis and it is the easiest to implement, no tests were performed to test this rule.

To support Rule 2 (that houses added on end branches need a flow reducer sized smaller than the house that comes after it) experiment houses 1, 2, 3, 5, 6, and 7 identified in Figure 10 were used. Experiment houses 4, 8, and 9 (Figure 10) tested Rule 3, that new houses placed in a group of all flow reducer sizes should be sized to match the size of the house closest in elevation.

To see which flow reducer size worked best and to verify the rules, the author ran simulations on every design file noting where she had to manually change flow reducer sizes to match the flow reducer size from the “All” design file. A summary of these results is presented in Table 23.

Experiment houses 1, 2, 3, 5, 6, and 7 all performed better (Experiments X1, X5, X6, and X7) or the same (Experiments X2 and X3) with the flow reducer size based on Rule 2 compared to using the size of the flow reducer installed in the closest house. This supports the validity of Rule 2.

The experiments performed to test Rule 3, X4, X8, and X9 showed mixed results. For experiment X4 and X8 the flow reducer size obtained based on the closest house was found to be better. In experiment X9, the size of the new flow reducer installed in the experiment house influences the flows of the surrounding houses differently. House P13 was found to experience flows smaller than 0.1 L/s less frequently with the flow reducer sized based on the closest house, while P14 experienced flows less than 0.1 L/s more frequently with the same one. These results show that Rule 3 is not valid in the Santa Cruz aqueduct and that in these areas it is better to install the flow reducer based on the closest house.

Table 23: Variations Simulation Flow Results Corresponding to Different Flow Reducer Sizes from Prediction, NeatWork Sized, and Based on Closest House

Experiment	Flow Reducer Size (in)			Nearby Flow Reducer Sizes Changed			Percentage <0.1 L/s in Simulations			
	Prediction	NeatWork	Closest House	House	All Size (in)	Experiment Size (in)	House	Prediction	NeatWork	Closest House
X1	7/32	1/4	none	N4	7/32	3/16	26	15	26	27
							28	0	0	6
X2	1/4	1/4	none	35	7/32	1/4	No Significant Differences			
X3	7/32	1/4	1/4	44	1/4	none	No Significant Differences			
X4	1/4	none	7/32	60	1/4	none	60	15	22	11
X5	3/16	3/16	7/32	60	1/4	none	60	12	12	23
X6	7/32	1/4	1/4	51	1/4	none	51	6	17	17
X7	1/4	1/4	None	--	--	--	56	11	11	30
X8	7/32	7/32	3/16	11	7/32	1/4	14	18	18	5
				12	1/4	none				
X9	1/4	none	none	9	5/32	7/32	13	33	27	27
				10	5/32	7/32	14	42	56	56
				11	7/32	none				
				12	1/4	none				
				15	3/16	1/4				
				16	3/16	none				

4.3 Audience for Decision Support Tool

The intended audience for the decision support tool created as part of this research is a local rural water committee in a developing world community. The reason to develop such a tool is because NeatWork was shown in the previous section not to be a viable decision support option for sizing flow reducers once a Peace Corps Volunteer (or other development worker) leaves the community because most community members do not have access to a computer.

As mentioned previously, in this geographical context, no technical experience is currently required to serve on a locally elected water committee, only the ability to read and write. However, during the time a Peace Corps Volunteer is in the community, she or he will be working with the water committee so they are expected to have the following training and skills: 1) participate in a water committee seminar of basic aqueduct principals, maintenance and leadership, 2) observe the aqueduct flow reducer simulation, 3) assist the volunteer in surveying the existing system, 4) know how to cut and mold PVC pipes, and 5) help fabricate and install flow reducers into the existing system.

Therefore, in order for a decision making tool to be appropriate to be left with the water committee members it needs to be: 1) relatively simple and easy to understand, 2) not relying on difficult mathematics, and 3) not relying on understanding of engineering hydraulic concepts such as available head.

4.4 Assumptions

This tool to size flow reducers was developed to assist the decision making of a local water committee. In order for it to work effectively, the following assumptions on aqueduct expansion have to be made:

1) Houses will be placed randomly though the system instead of creating a new branch with multiple houses
2) Houses will be placed within the existing distribution system (i.e., not farther away from the tank than any of the existing houses)
3) Houses will be added to the aqueduct based on normal population growth (more information on how population growth can be used to determine what a reasonable number of houses that will be added to the aqueduct during its lifespan is in Appendix F).

4.5 Tool to Size Flow Reducers

Based on the proceeding analysis and information, the author created a map tool to size flow reducers as presented in Figure 18. This map visually depicts the accepted Rule 2 by marking locations that follow that rule in different colors depending on flow reducer size. The color coating, makes it possible for those on the water committee to use the map. Using a map tool in Santa Cruz is culturally appropriate because the water committee is able to use it to size flow reducers without significant training or relying on skills they do not have. While maps are not widely used in their culture, the members of the water committee and community demonstrated an ability to use maps when they drew a community map for the author when she first arrived in Santa Cruz. They also showed understanding of the map tool developed for this research by properly identifying flow reducer sizes for theoretical future houses during the initial explanation of the tool. If the as-built aqueduct matched the original designed aqueduct, the map tool in Figure 18 would have been given to the Santa Cruz water committee.

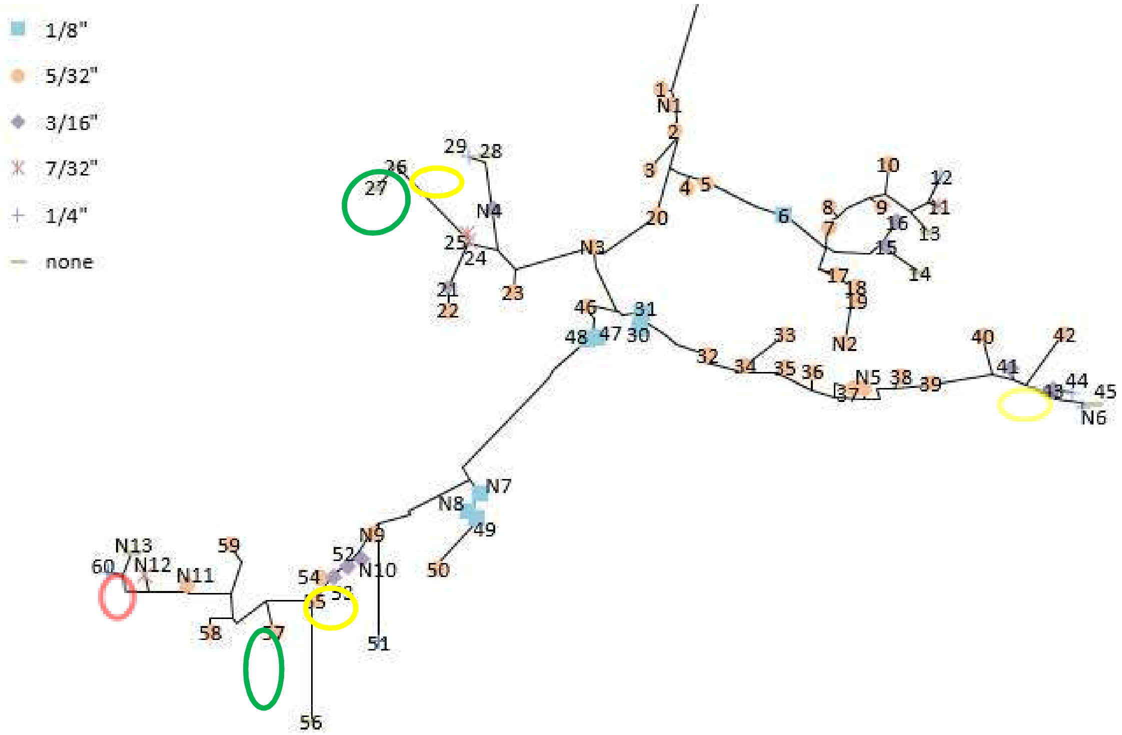


Figure 18: Final Decision Support Tool Created for the Originally Designed Santa Cruz Aqueduct Presenting Faucet Numbers and Locations where Flow Reducers Cannot Be Sized Based on the Flow Reducer Size of the Closest House (not to scale)

The following instructions were also translated and provided to the water committee: Locate where the new house will be on the map and determine the correct size of the flow reducer using the following rules:

1) If the house was included in the original design and marked by an N#, install flow reducers as depicted by the symbol.
2) If the new house is not in an oval, install the same size flow reducer of the closest house.

3) If the new house is in a green oval, install a 1/4-inch flow reducer.
4) If the new house is in a yellow oval, install a 7/32-inch flow reducer.
5) If the new house is in a red oval, install a 3/16-inch flow reducer.

4.6 Applying the Tool to the As-Built Aqueduct

Due to a variety of factors, the aqueduct that was actually built does not match the aqueduct the author initially designed or solicited funds to build. Some of these changes included moving the storage tank to a higher elevation, changing locations where the pipe was buried in order to cross a river at a shorter span that reduced costs associated with building a bridge, changing locations where pipes were placed to follow established footpaths rather than cutting through people's land, adding six additional houses to the design from the secondary aqueduct to help alleviate problems associated with the fact that the source for that system was drying up, and changing the design because of community input so everyone had individual connections to the main line rather than connecting to shared branches.

Due to changes in pipe placement during construction, the author used her engineering judgement based upon the original aqueduct design to install pipes that would allow for a functioning aqueduct. Midway through the project when the author believed she was aware of all changes, she created a new NeatWork design file, "Final Design", based on what was actually implemented in the field. She then used NeatWork to size the flow reducers on the as-built system verifying it still would have a high level of service. This design resulted in a NeatWork simulation with zero houses experiencing no flows or having flows less 0.1 L/s 25% of the time. The input tables and NeatWork summary report for the final design are in Appendix D. Small changes were still made during construction in regards to where homeowners wanted their individual lines to connect to the main line. The author decided these changes would not affect the level of service associated with the aqueduct or warrant the need to change flow reducer sizes, so she did not redo the NeatWork design to reflect these minor changes.

Some houses dropped out of the project because they could not attend a sufficient number of required work days or they found other adequate sources to create their own independent systems. In addition, other houses still have not paid their connection fees so are not currently connected. With 49 houses on the system including 2 houses not in the original design, the aqueduct is currently functioning and all users have a reliable water supply.

The as-built aqueduct is displayed in Figure 19. If the houses do not have lines connecting it to the main line it signifies that the house was included in the original plan but for some reason chose not to connect. The map also indicates where 9 locations that may connect to the aqueduct in the future, but were not included in the design because the author only became aware of them during construction. Two of these houses have already been connected.

The author created another topography “As-Built with Potential Connections” to analyze the flow reducer sizes needed for the potential connections not included in the design. However, since the pipe sizing was not originally sized by NeatWork, when input NeatWork failed to provide flow reducer sizes remotely close to what was installed in the field. Therefore, the author sized the flow reducers based on the rules determined from her analysis on the originally designed aqueduct. All of the houses fall in the middle of the aqueduct and should be sized based on the closest house. However, N8 and N6 are almost equal distant to two houses with different flow reducer sizes. A test was carried out in order to examine how the aqueduct would perform for both scenarios.

For house N8, the author ran simulations installing a 1/8-inch flow reducer matching house 41 and a 5/32-inch reducer matching house 43. In the simulations, the simulation with the 1/8-inch flow reducer resulted in slightly better results. Flows less than 0.1 L/s occurred less frequently, but there were no noteworthy differences. While the author indicates installing a 1/8-

inch flow reducer on the map left with the community, if the water committee installed a 5/32-inch flow reducer instead, it would not have mattered.

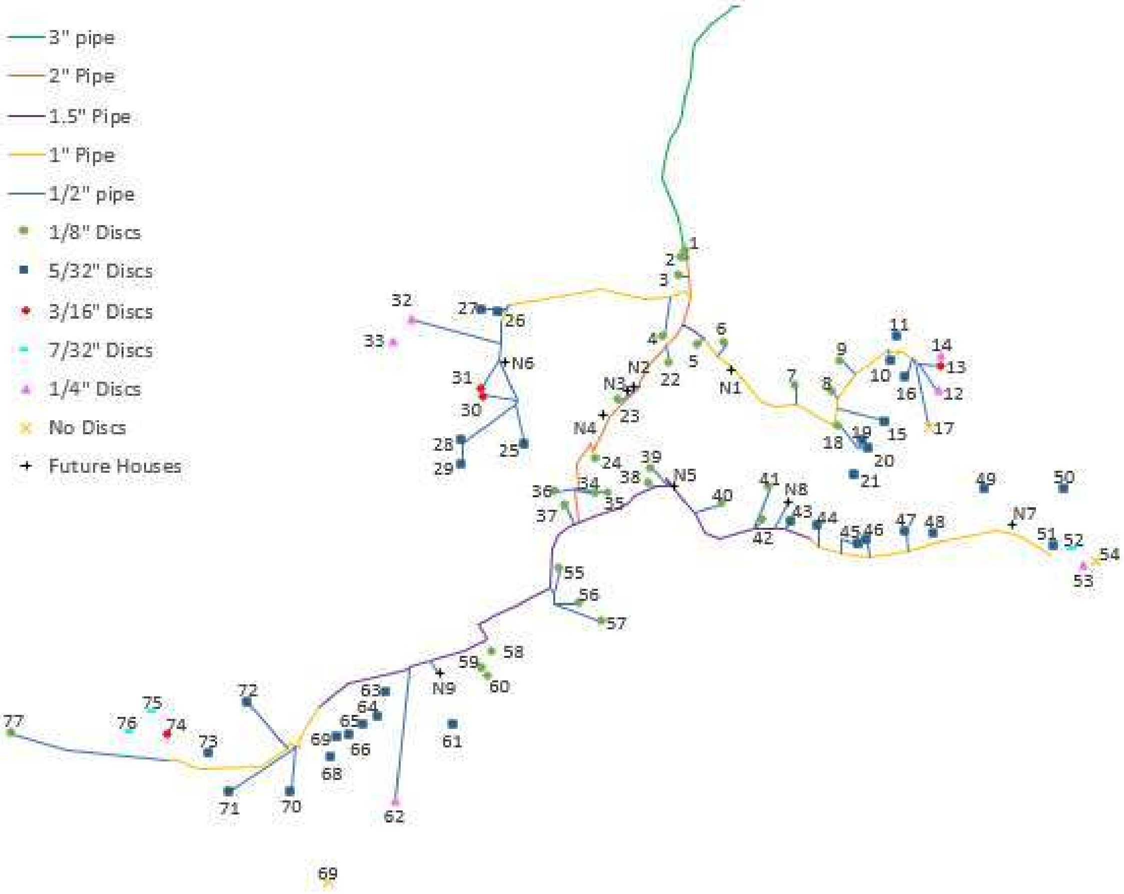


Figure 19: Map of As-Built Gravity Flow Water System in Santa Cruz with House Numbers and Flow Reducer Sizes from Final Designs (not to scale)

House N6 performed better with a 5/32-inch flow reducer matching that of house 26 compared to a 3/16-inch flow reducer matching house 31. While on the map, house N6 appears equally distant from houses 26 and 31, when in the field it is clear it is closer to house 31. It also is at a lower elevation than both house 26 and 31. Based on the elevation difference, the author correctly predicted that N6 should have a 5/32-inch flow reducer, but she believes the water committee would have installed a 3/16-inch flow reducer resulting in a lower quality of service in the aqueduct as summarized in Table 24.

Table 24: Simulation Differences between Varying Flow Reducer Sizes for House 6 in As-Built Aqueduct

House	min flow (L/s)		% flows less than 0.1 L/s (%)	
	5/32"	**3/16"**	**5/32"**	**3/16"**
10	0.00596	0.74	17	27
11	0	0	51	61
14	0.0639	0.0596	26	50

While an ideally sized flow reducer has better results, this shows that there are some houses that will not follow the easily recognized guidelines and communities will install flow reducers that may not be ideal. This may hurt some houses, but it will not destroy the quality of service of the aqueduct. It can be avoided if the author can determine where the future houses will be and include them on the map as is what happened in Santa Cruz. The author will reflect the ideal flow reducer sizes for houses N8 and N6 as well as the other new houses on the map to be provided to the water committee.

The author analyzed how the new design would affect the circled locations as presented in Figure 18, the original tool she created. This time, she also took into account the likelihood of houses being built in these regions based on her personal knowledge of the families. In the following analysis, the house numbers match those from Figure 19.

Initially there was a circle close to the end branch including houses 51-54. However, none of these houses are currently connected to the aqueduct and only house 52 expressed interest in connecting. If a house is built between house 51 and 52, it would most likely require a 3/16-inch flow reducer assuming all the houses are connected. However, with few houses connected at the end of the line, the size of the flow reducer installed in that area will have even less of an impact. A circle may not be necessary.

Looking at end branch with houses 73-77, one notices that an additional house was added even though the residents originally wanted to stay on their independent system. House

77 is actually significantly lower in elevation than house 75 and 76, hence the smaller flow reducer size. If a house were to be built between house 75 and 76, it would most likely be a flow reducer sized at either 5/32-inch or 3/16-inch depending on elevation. Marking two different sizes in an area so close together becomes more complicated for the local water committee, especially when passed down to future committees who were not trained by the author. The author does not believe it is very likely a house will be built there because it is the land of the family that lives in house 77 and they have no children making the circles potentially more confusing than necessary.

In the new design, no flow reducer sizes are skipped between house 73 and 76. Therefore, unlike in the original tool, it is appropriate to size any new houses built in this area based on the size of the flow reducer of the closest house.

The circle that was on the map between the existing house 26 and N6 is no longer relevant because it no longer is at an end branch. Also, the circle that was before house 32 seems irrelevant because this land is being used as a cooperative farm. It is unlikely that anyone will build a house there and it has its own system from an open stream to water its crops and give to the animals. Therefore, it will not require its own connection either.

This leaves the circles leading to houses 62 and 69. While these circles would be relevant, adding them increases the complexity of the tool, but would only minimally affect the aqueducts serviceability especially since house 69 is not currently connected. After working with the water committee on installing the flow reducers and seeing how the current aqueduct is working, the author believes that having a few flow reducers installed of non-ideal size will be okay. Therefore, she opted for the simplest map option and removed the circles leading to houses 62 and 69 as well. She renumbered the map as shown in Figure 20 and left copies with different individuals of the water committee with the following translated instructions and list of the owners' names as they correspond to each number. She also gave them a letter explaining the importance of continually installing flow reducers.

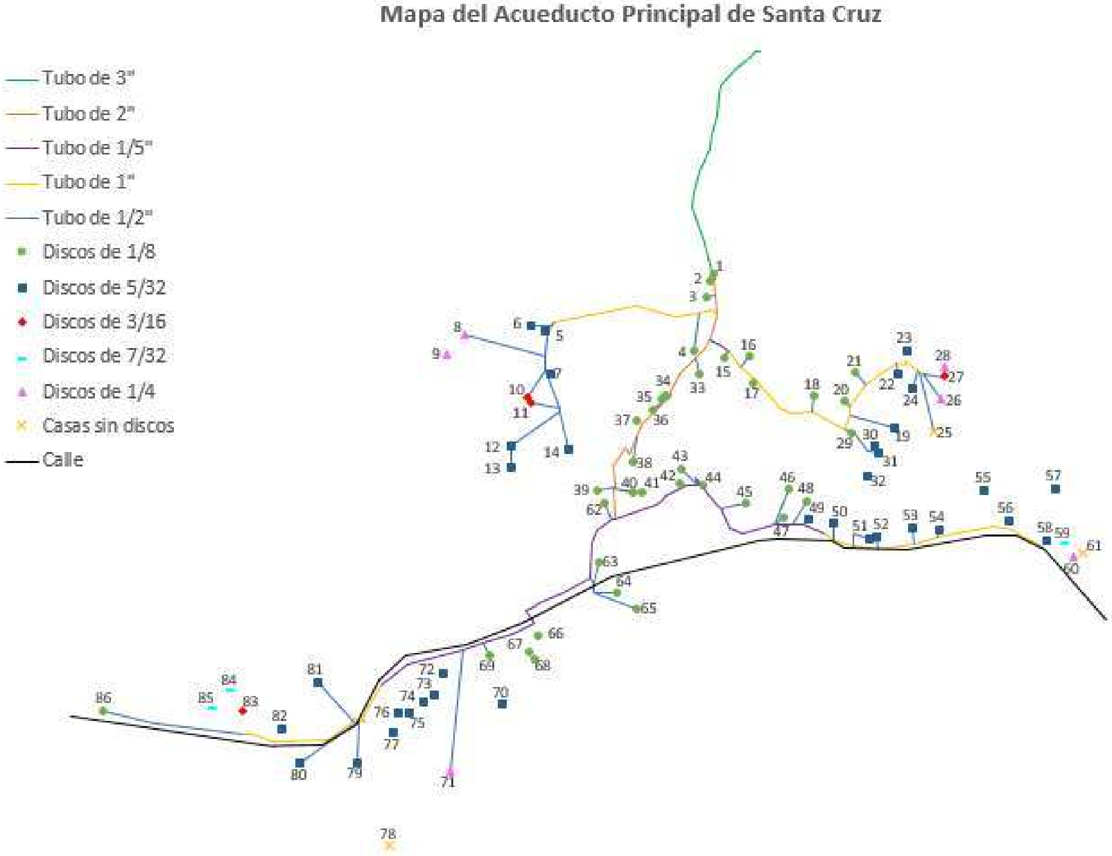


Figure 20: Map with House Numbers and Flow Reducer Sizes Provided to the Santa Cruz Water Committee (not to scale)

The instructions to use with the map in Figure 20 are:

1) If a new house is shown on the map, install the flow reducer as indicated.
2) If a new house is not shown on the map install the same size flow reducer that the house closest to it has.

Along with the map, the author also left many prefabricated flow reducers of all sizes in Ziplock™ bags labeled with the flow reducer size. Inside, was also a piece of paper colored to match the symbol on the map as seen in Figure 21.

Figure 21: Picture of Extra Flow Reducers Provided to the Santa Cruz's Water Committee

Chapter 5: Conclusions and Recommendations

Many Peace Corps Volunteers in Panama use flow reducers in gravity flow water distribution systems they improve and build. While flow reducers help equalize the flows between houses, they need to be installed in any future connections to ensure systems remain reliable. The objectives of this thesis were: 1) Use the NeatWork model to determine how the addition of houses to an existing gravity flow water system will affect its serviceability, 2) Develop an easy to understand method to teach community members from Santa Cruz (Panama) in order to enable community members to correctly size flow reducers for houses added to the water system in the future, and 3) Provide guidance to future Peace Corps Volunteers and development workers to ensure they are able to design and implement sustainable flow reducer projects in their respective communities. These objectives were designed to disseminate the knowledge generated in this research to two distinct stakeholders: a water committee comprised of community members whose job is to maintain the aqueduct with Objective 2 and development workers who will plan and lead the implementation of the projects as well as train local water committees through Objective 3.

5.1 Conclusions from Objective 1

As expected, as more houses are added to an existing aqueduct, the service quality declines. However, the declines in serviceability can be reduced if community members continually install flow reducers during the expansion. The closer the installed flow reducers are to their ideal size, the smaller the effect on serviceability will be. Objective 2 explores how to ensure the right size flow reducers will be installed.

As houses are added, the ideal pipe sizes will also increase in certain parts of the system. While it is impractical, to design a system that would require pipes to be changed after installation, the designer can include future installations in the initial design to create a more robust system from the beginning. Before surveying, the system designer should talk to their community about where houses may be built in the future and include these and all houses in construction in the original design. This will create an aqueduct design with some pipes larger than those required at the moment, but it will allow for expansion without hurting serviceability, helping long term sustainability.

Some future connections will be missed as it will not be possible to correctly identify where and when houses will be built. Although the ideal design will change, the author concludes that this is acceptable as desired changes within the pipe network are minimal and serviceability remains good as long as flow reducers are continually installed.

5.2 Conclusions from Objective 2

Due to the complexity of water distribution systems and the limited technical knowledge of water committee members, it was not possible to create a uniform decision support tool to use with all distribution systems. However, based on the analysis, a map can be created for individual aqueducts and left with the community's water committee as presented in Section 4.4. The map presents the correct flow reducer size determined by NeatWork for any known potential connection as well as well as providing instructions on how to size houses that were not included in the original design.

In the Santa Cruz aqueduct, the author observed that end branches that slope upwards and areas without all the flow reducer sizes are more sensitive to flow reducer sizes being different than that of the closest house. She also noted that some end branches were similar in topography, but differed because while on different branches the region had all the flow reducer sizes which might lead to sizing houses based on the flow reducer size of the house at the closest elevation.

Based on her observations, the author developed three rules to size flow reducers which were then tested with experimental houses. In the majority of the aqueduct system studied here, any new house can have the same size flow reducer of the closest house. This was seen in the original analysis when eight of the thirteen new houses had the same flow reducer size when sized with NeatWork and by sizing based on the flow reducer size of the closet house. Installing flow reducers based on the closest house became the basis for Rule 1. With the results from this analysis on the experiment houses, it can be concluded that Rule 2 is valid; in the sloping upwards end branches, flow reducer sizes closer to the tank should be smaller in size than the house after it. Rule 3, that in some areas flow reducers should be sized based on the flow reducer size installed in the house that is closest in terms of elevation, was rejected based on the experiments.

In order to turn the rules into a tool that can be used by the local water committee a map tool was created that visually depicts them. It allows water committee members to size flow reducers themselves making it culturally appropriate.

5.3 Conclusions from Objective 3

A guide was developed for sustainable flow reducer projects that was disseminated for future volunteers based on the research for this thesis and the author's experience from manufacturing and installing flow reducers in the Santa Cruz community. The guide is reproduced as Appendix A and the main points are summarized below:

1) Include all potential future connections considering houses with independent sources, houses under construction, and spots where houses may be built in the future.
2) Teach the entire community, not just the water committee about the importance of flow reducers and include all community members in the fabrication of the flow reducers.

3) Fabricate extra flow reducers of all sizes and leave them with the water committee. It will be easier to install them in future connections if they are already made.
4) Create a map of the aqueduct clearly showing the location of existing houses and what size flow reducer each house has. Include any potential future connection on this map. Explain how to use the map to the water committee to size the flow reducers of future houses based on the flow reducer size of the closest house.
5) Constantly reinforce with the water committee and all community members that if they want the aqueduct to keep working, all new connections need flow reducers.

5.4 Recommendations for Future Research

During this research, the author assumed the NeatWork default values were appropriate to use based on the fact that in implemented aqueducts, the users were pleased with the end results. However, more work should be done to confirm the accuracy of the model. Ideally this would be done by measuring flows in the field and comparing them to the flows provided by NeatWork. For this field validation study, a simulation could be run with only one trial so there would be only one flow condition occurring throughout the aqueduct. Then based on the faucets used in this simulation, those faucets could be opened simultaneously and the flow from each faucet could be measured by timing how long it takes to fill a container of known volume at each faucet. This could be repeated for various simulations to verify the NeatWork model is accurate. However, this would be extremely difficult to coordinate in the field because multiple faucets spread throughout the community would need to be turned on at the same time and others would not be able to use water at those times. The default value of fraction of faucets opened is 0.4 so for the tested aqueduct of 73 houses, 29 houses would need to be opened during the measuring of flows and 44 houses would not be able to use their faucets during the field testing.

Another option would be to compare the flows if only one faucet was opened. In NeatWork an individual faucet simulation could be run and in the field flow could be measured for individual faucets. To guarantee only one faucet would be in use during the field test without disrupting the daily lives of the community members it is recommended that flow from the designated faucet be measured at night when most of the community is sleeping.

Another consideration when collecting flow data in the field would be the height of the water in the tank. The NeatWork model assumes that the level of water is at the elevation of the tank outlet where it provides the minimal head. The outlet is typically located close to the bottom of the storage tank. Most likely the storage tank will have more water in it providing additional head and potentially greater flow in the distribution system. Two simulations could be run in NeatWork changing the elevation of the tank to match the elevation of the outlet and the overflow to calculate the minimum and maximum flow at each faucet. The measured flow should fall in this range of values. If this range is too large to verify the accuracy of the results, it could also be coordinated for the water levels in the tank to be monitored while flow measurements are being collected and changing the height of the tank to match this height before running the NeatWork simulation. Collecting flow measurements in the field would help to validate NeatWork's ability to provide accurate flows.

To further validate this research, a sensitivity analysis should be run to test the two most important input values which are expected to be the service factor, which is used during the design phase and the fraction of faucets opened, which is used during the simulation phase. These two variables are related to the serviceability of the aqueduct.

A larger service quality factor corresponds to a more reliable aqueduct, but it will also be more expensive. The design engineer typically wants to use a value that provides sufficient water without wasting money. Also, as more faucets are opened, the serviceability of the system will decrease. While it is more economical to design an aqueduct assuming all of the faucets are not open at the same time, it is important that the fraction of faucets open is an accurate representation of community behavior. If it is too low, the model will show the aqueduct providing everyone in the community with water when in reality users may face low or no flow situations. Along with a sensitivity analysis, surveys of users could be conducted collecting information regarding when people use water and times when the flow is too low.

This thesis works under the assumption that houses will be added to the aqueduct, and if they are properly sized with flow reducers, the aqueduct will continue functioning at a reasonable level of service. However, at some point too many additional houses will cause the aqueduct to be undersized and houses will cease to have a reliable flow. More research should be conducted to determine what this limit is and potentially determine how Peace Corps Volunteers can alter initial designs to compensate for the additional houses that may be added in the future after Peace Corps has left the community. Also, work could be done to determine how to add branches to an aqueduct rather than having new houses randomly placed throughout the distribution network.

While the author was able to create a map tool for the Santa Cruz community, more work needs to be done to determine if there is a generic way to create map tools for other communities regardless of aqueduct size and layout. Depending on results and if it is deemed necessary to use the map tool instead of sizing based on the closest house, guides should be developed for future Peace Corps Volunteers to help them recreate the map tool as presented for their respective communities.

Monitoring and evaluation needs to be continued to see how communities respond to the flow reducer projects years in the future. Are they installing flow reducers as houses are added? Are they sizing them correctly? Have flow reducers been removed from the system? Environmental Health Volunteers have been working in Panama since 2002. While it is unknown exactly when Peace Corps Volunteers started installing flow reducer projects, the author knows they have been utilized since 2011 making some systems at least 5 years old. For these systems, data can be collected about how the aqueduct has expanded since initial implementation, if the aqueduct is still operating at a reliable level of service, if flow reducers have been removed for any reason, if flow reducers have been installed in any new connections, what sort of trainings were done relating to flow reducers, etc. In a few years monitoring and evaluation should be performed in Santa Cruz and other communities that have implemented flow reducer projects under the guidance of this research. It should be investigated what the volunteer did to assist the water committee with flow reducer maintenance and see how the water committee is doing. Do they still use the map tool when houses are added? Was the information successfully passed down to future water committee members? Monitoring and evaluation will be required to determine how sustainable the projects actually are and will allow for improvements to be made to the volunteer guide and community map tool to make future projects more successful.

A challenging aspect of this research was dealing with NeatWork. While it is a great tool for the design of distribution systems in this setting, the software is outdated and can be frustrating to use. The latest version of NeatWork was released in 2010 and has not been updated while computer processors have. Therefore, there are some compatibility issues causing NeatWork to freeze frequently. Inputting pipe constraints is also a tedious process as the sizes need to be manually imput for each segment length. While it is still a viable option with many advantages, it may be worthwhile to think about contacting Agua Para La Vida to help update NeatWork to make it more user-friendly.

It might be beneficial for other researchers to look into adapting other software such as EPANET or GOODwater for situations like explored in this research. EPANET is another publicly available computer software created for use in the developed world on larger systems. The author knows some Peace Corps Volunteers have used EPANET to aide in their aqueduct design, but is not sure exactly what capabilities it has in regards to sizing flow reducers and running simulations.

GOODwater was developed by a Master's International Peace Corps Volunteer to optimize pipe sizing utilizing the solver function in Excel. It currently does not allow for valves or flow reducers to be utilized in the design. A future researcher would need to modify the GOODwater software in order to apply it to similar research. If either EPANET of GOODwater can be applied to flow reducer research, it might make further analysis faster.

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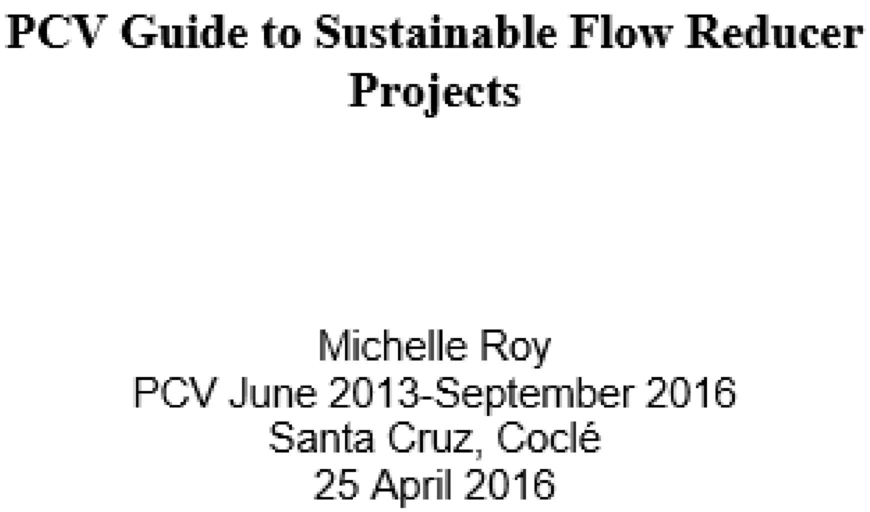
Appendix A: Peace Corps Volunteer Guide to Sustainable Flow Reducer Projects



PCV Guide to Sustainable Flow Reducer Projects

Michelle Roy
PCV June 2013-September 2016
Santa Cruz, Coclé
25 April 2016

Contents

Introduction

Flow reducers also known as orifices in NeatWork or discos de controlar in Spanish are little plastic discs that help ensure an equal distribution of flow in a gravity-fed aqueduct. While logical to install, you won't find them mentioned in any of the other design guides. NeatWork uses them, but doesn't provide much information on them other than the size. If you opt to design a new system or are trying to trouble shoot an existing aqueduct and want to use NeatWork to help with your design, there is a good chance that you will need to use flow reducers so I hope this guide can be useful in the planning and implementation stages of your project, and more importantly, to help make sure your community will continue to install flow reducers after Peace Corps leaves.

Purpose of Flow Reducers

The goal of having flow reducers installed into an aqueduct is to ensure an equal distribution of flows between houses. Flow reducers can be installed into existing systems to fix inequalities of flows or in new systems to ensure a fair distribution. Water is lazy and will flow out of the system in the easiest path. This normally occurs at houses close to the tank and at lower elevations, or in engineering speak, the houses farthest from the HGL. Flow reducers minimize this problem by making it equally difficult for the water to arrive at every house. The houses where water will easily flow too will receive a disc with a small hole (hard for water to pass through) where the houses that are already hard for the water to get to will receive discs with larger holes or no disc at all. Ideally, with flow reducers installed and a properly sized distribution system all users will have continuous water access.

Surveying

The actual methods of surveying are the same if you want to add flow reducers or not. However, if you want to make your aqueduct more sustainable I highly recommend including all current houses and any houses under construction that may want to connect to the aqueduct in the future in your initial survey. It is easier to survey everything one time rather than going back and surveying for additional houses. Also, all potential future houses should be included in the design for your project. This will make the aqueduct slightly more robust than it needs to be, but will give it a longer life span with good serviceability for all users.

Sizing of Flow Reducers with NeatWork

Luckily, NeatWork can size flow reducers for you once you have successfully surveyed your system. There are other how to use NeatWork guides available so I won't give too much detail about that, but offer so suggestions directly related to flow reducers.

Most drill bits are available in English units when NeatWork is in metric. Check your local hardware store to make sure all the sizes are available and if you cannot find a certain size don't include it in your design. In order to make sure your needed hole sizes match your drill bits, change your default orifice values before you have NeatWork design your system. To do this:

1) Open NeatWork
2) In the database tab, click "Edit Database"
3) Go to the orifice tab
4) Change the diameters in the table. The conversions from standard drill bit sizes to metric units are presented in Table 1.

Table 1: Conversion of Drill Bit Sizes to Metric Units

Flow Disc Diameter	
(in)	**(m)**
3/32	0.002381
1/8	0.003175
5/32	0.003969
3/16	0.004763
7/32	0.005556
1/4	0.00635

5) Save your database
6) Before you start your design check to make sure you are using the right database. NeatWork is finicky and does not always save correctly.

If once you have a design and are unhappy with the results because NeatWork is predicting the house will either have too high or too low of a flow, you can manually change the flow reducer size by:

1) In your table that gives you the orifice size locate the faucet in question.
2) Click on the commercial orifice for that faucet and adjust the flow reducer selecting the size bigger or smaller in table one. The table should turn blue.
3) Click the green check mark. The table should turn white.
4) Save the design and close out of NeatWork. (I find the simulations are more likely to run if the program is opened again after the changes are made).
5) Reopen Neatwork and check to make sure the changes saved.
6) Re-run the simulation.
7) Continue adjusting flow reducer sizes if necessary.

Materials and Tools for Flow Disc Fabrication

- ☐ **PVC pipe** You can make a lot of discs out of a short section of pipe. 3 or 4 feet of scrap pipe should be sufficient. The size of the pipe does not really matter. The smaller pipes (1/2-in and 1-in) are harder to mold into flat section while larger pipes (3-in to 4-in) are thicker so harder to punch out the disc. I used scraps from 1.5-in, 2-in, and 2.5-in pipes.
- ☐ **Hack saws (Segetas)**
- ☐ **Vegetable Oil** Afterwards you can save the oil for more thermoforming, but make sure no one uses it to cook with. It will contain toxins from the PVC pipe.
- ☐ **¾-in galvanized pipe (Tubo galvanzado)** Have the ferretería cut it into 1.5-ft sections for you.
- ☐ **Heat source** Lug your stove to the work place or have your community collect firewood for you so you have a way to heat the oil and the metal pipes.
- ☐ **Two Flat Surfaces** Basically anything that will allow you to flatten your PVC. Cinderblocks work well.
- ☐ **Files, Knives, Scissors (Limas, cuchillos, tijeras)** The files are crucial, but you can use a combination of tools to file the discs.
- ☐ **½" PVC uninons (Uniones de ½)**
- ☐ **Drill (Broca)**
- ☐ **Drill bits (Juegos de broca)** Make sure you have all the sizes that are included in your design.

Fabrication instructions

1) Cut the pipe into short sections (approximately 4 in wide) and cut vertically through the entire section. The actual size of the pipe segments does not matter as long as the sections can fit in the container that will be used to heat the oil.

2) Emerge the PVC in hot oil until it is moldable, but does not show signs of burning You should not observe bubbles or color change in the PVC.

3) Place the hot and moldable piece of PVC between two flat surfaces such as a concrete floor and a cinderblock until it cools. Make sure that the PVC does not fold upon itself, but is actually flat between these two surfaces.

4) Heat a ¾" metal pipe (the length does not matter, but 1.5-ft pipes work well) by placing it in the fire. When it is hot, vertically press down while rotating the pipe on the flat pieces of PVC to punch out a disc.

5) File down the edges so that if fits inside a 0.5-in pipe union. In Santa Cruz, community members used a combination of pocket-knives, scissors, and metal files to reach the desired size.

6) Use an electric drill and the proper size drill bit to drill bit to create a hole in the middle of the disc. It can be a bit of a challenge to make sure that a complete circle is cut rather than a more of a figure 8 shape that matches the curve of the drill. I found that it works better to pulse the drill at the beginning and then make sure the disc goes completely up the bit to the circle section. Heating the drill up by drilling it into wood also made it easier to scratch off the excess material on the drill bit while removing it. Whatever method you use, you want the disc to be able to move along the drill bit freely (ie without having to rotate it), but not larger than the actual drill bit.

7) Mark the discs and properly store them in separate marked containers based on hole size.

Materials and Tools for Flow Disc Installation

- ☐ **Hack Saw** (Segeta)
- ☐ **½" PVC unions (Uniones de media pulgada)**
- ☐ **Flow Reducers (Discos de contoriar)**
- ☐ **Rags (Trapas)**
- ☐ **PVC Glue (Pegamiento)**

Installation Instructions

The installation of flow reducers itself is a simple process, however the installation of all the discs to an existing aqueduct will take organization. All the flow reducers should be installed on the same day. If only installed in some houses, these houses will not have sufficient water while the other houses still do not have their disc which might cause resentment to the discs or the removal of the discs. If working with community members, a system needs to be put in place to ensure the right size disc is installed. I gave my team captains discs in baggies with the names of the houses written on the outside of the bag that were to get that size disc.

1) Close the tank or control valves within the system so that water is not flowing through the pipes where flow reducers are to be installed.

2) Cut the PVC pipe where the flow reducer is going to be installed. NeatWork does not provide specific guidance on where the disc is supposed to go. My system has some discs in the vertical pipe leading to the faucet, in the horizontal pipe a few meters away from the faucet, and also in the horizontal pipe a few meters after the control valves. It does not seem to make a difference in performance.

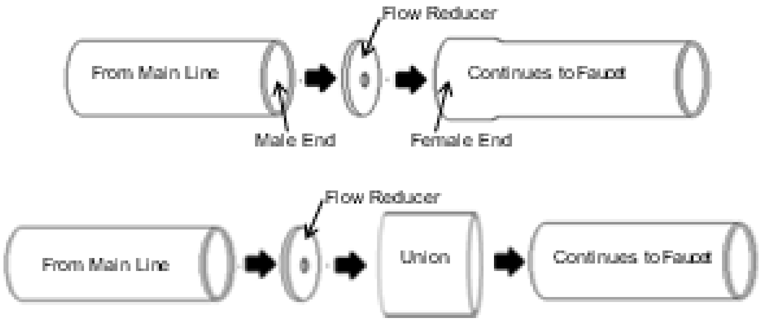
3) Clean the pipe with a rag to remove any dirt.

4) Place the flow reducer of the proper size in the union on the side where the water comes from so the water will push the flow reducer against the ridge of the union.

5) Glue both sides of the union to the cut pipe.

6) Reopen the water at least 15 minutes after the last disc is installed. The pressure change from the disc makes it easier for the tubes to come undone if the glue is not dry.

Alternatively, in a new system, discs can be placed directly into the head of the pipe before the faucet.



Flow Reducer Maintenance

The holes in flow reducers are small and if dirt is flowing through your pipes it is possible that the flow reducers will become clogged. If the source and the rest of the aqueduct are well protected this is unlikely, but if it does happen the flow reducer can be cleaned out. You will know a flow reducer is clogged or partially clogged if a house does not have water or very little water when it normally had more and if the nearby houses still have water as normal.

To clean a clogged flow reducer, cut the pipe 2-3 inches away from the flow reducer on the upstream side. Using your finger, a stick, a wire, or anything similar remove all the debris that might be blocking the hole. Reconnect the pipe with PVC glue and a union or a thermoformed piece of pipe.

Capacity Building

Capacity building is essential to a successful flow reducer project especially if they are being installed in an existing system. Some houses that are low in elevation or close to the tank may experience a lesser flow after the flow reducers are installed. Therefore, it is your job to teach them that the discs are necessary in order to allow everyone to have water. Even if they have less flow than before, they still will have enough water for their daily needs so they should not remove the flow reducers.

The aqueduct session on flow inequalities is great to teach not only water committee members, but the entire community about flow reducers. The whole charla with a fun dinamica is in the Water Committee Seminar. Even if you do not do a full water committee seminar, I highly recommend doing this demonstration with everyone involved in your flow reducer project. Even once the community members, are educated on flow reducers and believe in the idea, they might be worried about the size of the hole. Once community members saw the discs, they did not believe that the water would pass through such a small hole. Others were in agreement with the idea, but did not believe that their house should have a disc because it was higher than some houses. These concerns are very normal among community members. I eventually gave up trying to explain away their concerns, and resulted in telling them that we needed to install all of them to test it and If there were problems I would remove them. I than was very adamant, that if anyone was unhappy with the water situation once the aqueduct was connected, they needed to talk to me before they did anything. This worked to get them to help me install the discs.

When installing the flow reducers make sure that the community knows how to install the discs themselves. Talk about the proper way to clean them if they do become clogged as well. Continually reinforce the idea, that all the houses need flow reducers to make sure that everyone has water and that no one should ever remove their flow reducer.

sizes are present, and in places where the houses are spread out. My master's thesis investigates how to create better tools to leave with the water committee in cases where sizing based only on the closest house may not be enough. If you would like a copy of the thesis, please e-mail me at michelleroy919@gmail.com. Soon it will also be available at USF scholarly commons online, http://scholarcommons.usf.edu.

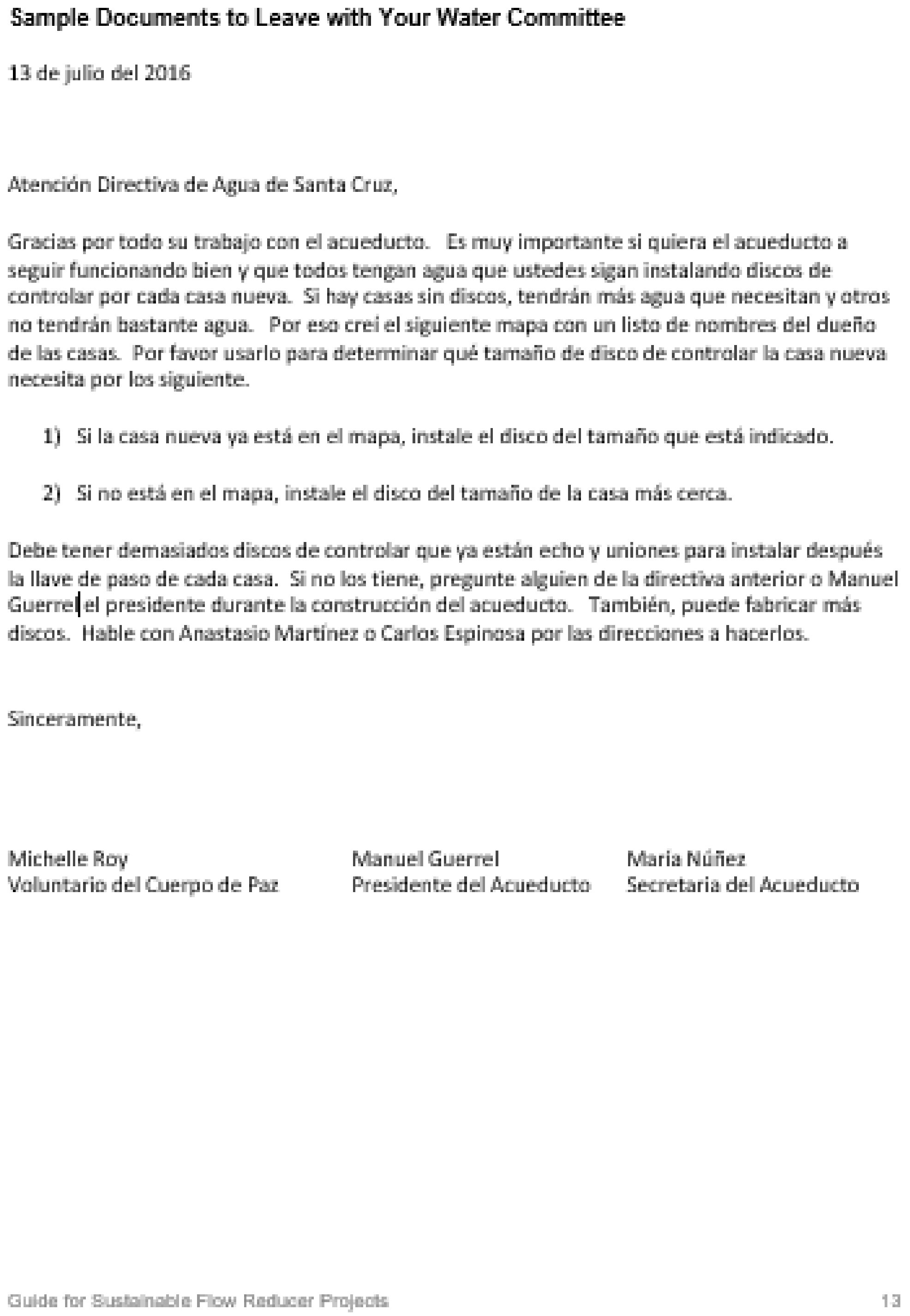
Future Installations

For the sustainability of the aqueduct, the most important thing is that flow reducers are continually installed as houses are added to the aqueduct in the future. If flow reducers are not installed the serviceability of the aqueduct will decrease and the farthest and highest houses will not have a continual water supply as intended. While the serviceability of the aqueduct remains highest if the ideal flow reducer sizes are installed, as long as a flow reducer that is close to the ideal size is installed, the drops in serviceability should be undetectable. Therefore, I believe the easiest way for community members to size flow reducers will be to install the same size flow reducer that the closest house has.

While the idea is not difficulty, you need to make sure the water committee can figure out which size disc is installed in each house. I made a map using the graphing features of excel and represented each house with a different icon depending on flow reducer size. The map should include every house that is currently connected to the aqueduct and locations of any potential houses included in your original design. Each house is than numbered and connects to a list of names that shows the name of the owner of the house and the size of the disc. These documents along with a letter explaining the importance of flow reducers and the instructions on how to use the map to size flow reducers was left with the water committee I worked with, with the intention that it will get passed down to the future water committees. A sample of these documents that I made for my community are included in the next section.

Also, it is recommended that you leave already fabricated flow reducers with the water committee. Put them in bags and label them with the same symbols that are used on the map. If extra discs are not going to be left with the community, make sure they at least have the tools and the ability to make more discs themselves.

In some aqueducts, sizing flow reducers based on the size of the closest house may not result in aqueducts with high serviceability. Flow reducers sizes are especially vulnerable to size changes at the end of branches, on upward slopes, in areas where not all flow reducers sizes are present, and in places where the houses are spread out. My master's thesis investigates how to create better tools to leave with the water committee in cases where sizing based only on the closest house may not be enough. If you would like a copy of the thesis, please e-mail me at michelleroy919@gmail.com. Soon it will also be available at USF scholarly commons online, http://scholarcommons.usf.edu.



Sample Documents to Leave with Your Water Committee

13 de julio del 2016

Atención Directiva de Agua de Santa Cruz,

Gracias por todo su trabajo con el acueducto. Es muy importante si quiera el acueducto a seguir funcionando bien y que todos tengan agua que ustedes sigan instalando discos de controlar por cada casa nueva. Si hay casas sin discos, tendrán más agua que necesitan y otros no tendrán bastante agua. Por eso crei el siguiente mapa con un listo de nombres del dueño de las casas. Por favor usarlo para determinar qué tamaño de disco de controlar la casa nueva necesita por los siguiente.

1) Si la casa nueva ya está en el mapa, instale el disco del tamaño que está indicado.

2) Si no está en el mapa, instale el disco del tamaño de la casa más cerca.

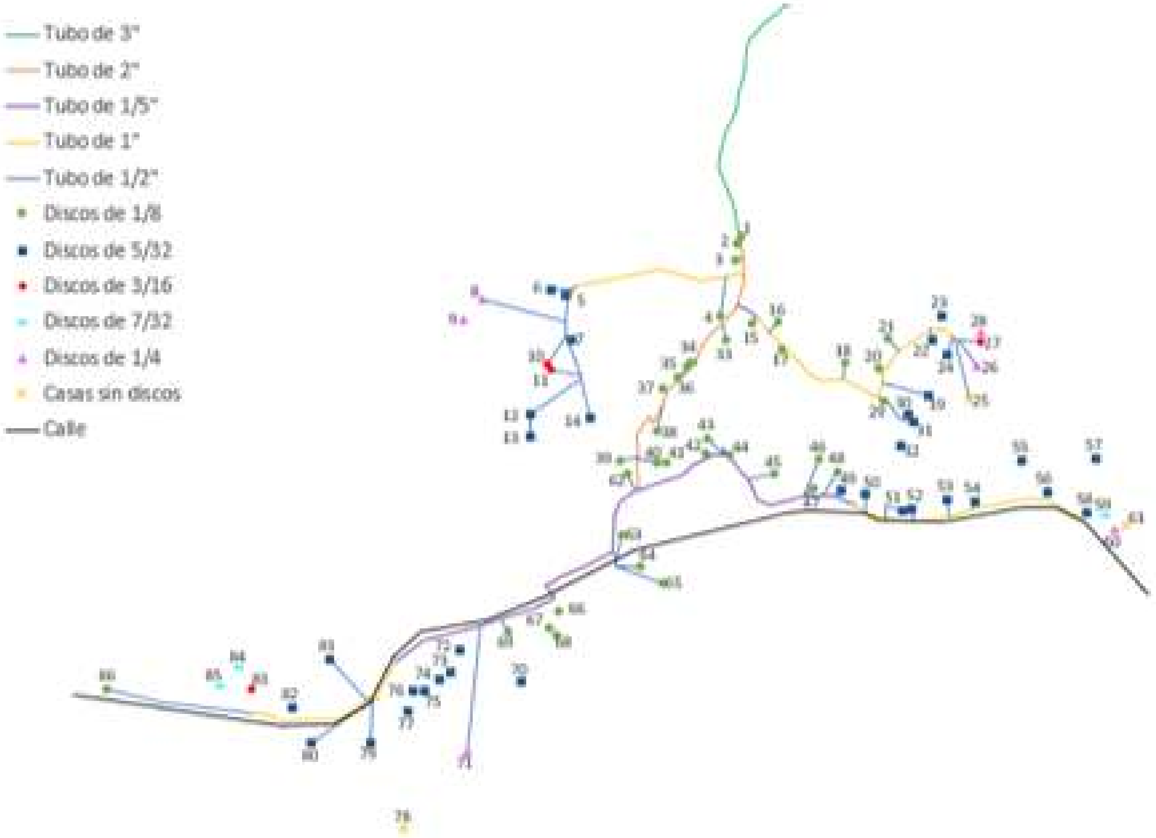
Debe tener demasiados discos de controlar que ya están echo y uniones para instalar después la llave de paso de cada casa. Si no los tiene, pregunte alguien de la directiva anterior o Manuel Guerrel el presidente durante la construcción del acueducto. También, puede fabricar más discos. Hable con Anastasio Martínez o Carlos Espinosa por las direcciones a hacerlos.

Sinceramente,

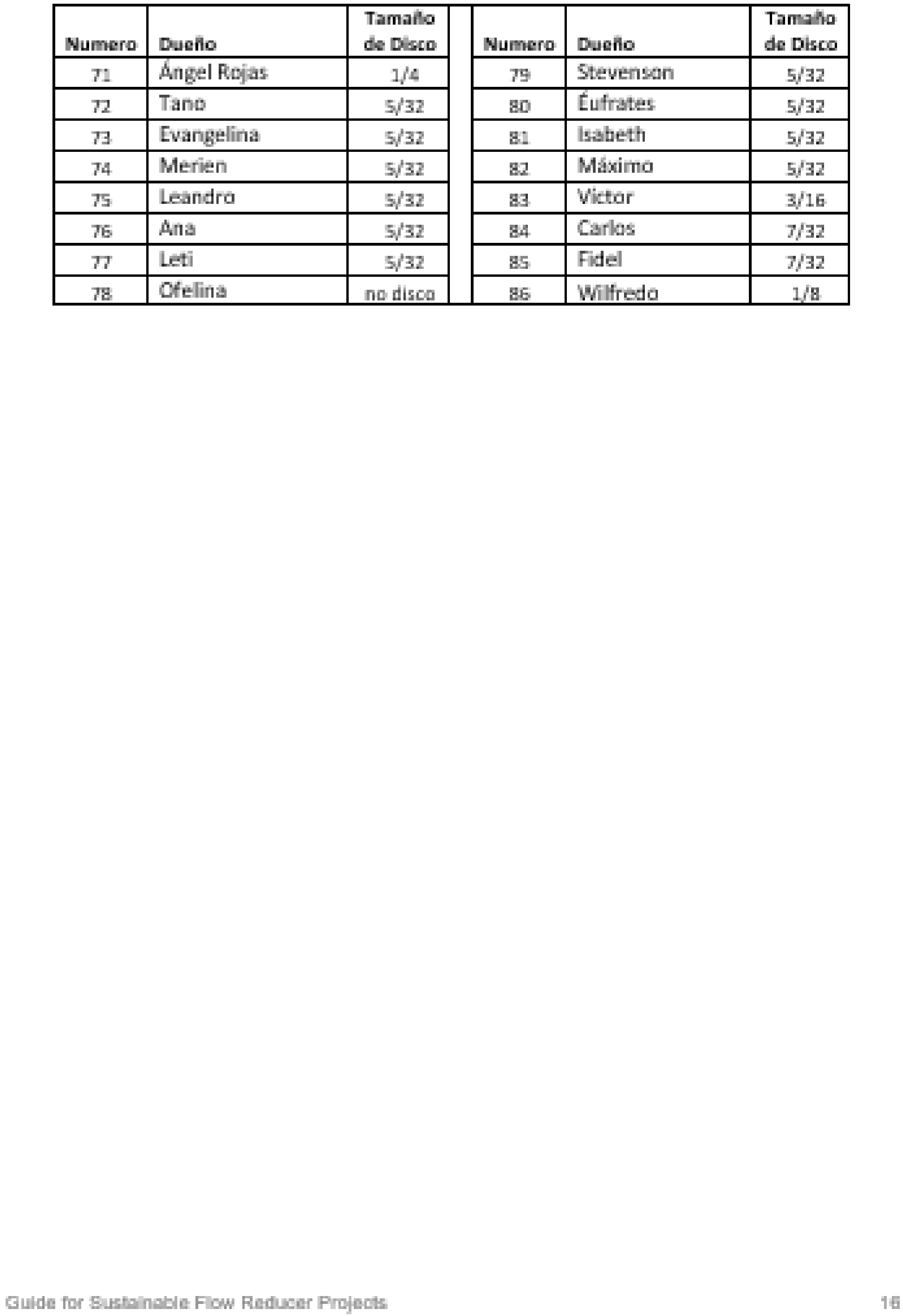
Michelle Roy	Manuel Guerrel	Maria Núñez
Voluntario del Cuerpo de Paz	Presidente del Acueducto	Secretaria del Acueducto

Guide for Sustainable Flow Reducer Projects 13

Mapa del Acueducto Principal de Santa Cruz



Numero	Dueño	Tamaño de Disco	Numero	Dueño	Tamaño de Disco
1	Gilberto	1/8	36	Honorio	1/8
2	Gilberto "Chachin"	1/8	37	Nerys Guerrel	1/8
3	Edilsa	1/8	38	Javier	1/8
4	Luis Carlos	1/8	39	Juan Morán	1/8
5	José Guerrel	5/32	40	María Rodriguez	1/8
6	Manuel Guerrel	5/32	41	Trinidad	1/8
7	Granja	5/32	42	Diana	1/8
8	Eleutino	1/4	43	Anastasio	1/8
9	Lorenzo	1/4	44	Maslenis	1/8
10	Yarela	3/16	45	Goyo	1/8
11	José Oliberto	3/16	46	María Martinez	1/8
12	Eduardo	5/32	47	Isabel	1/8
13	Valerio	5/32	48	William	5/32
14	Darío Morán	5/32	49	Mariana	5/32
15	Santo Martinez	1/8	50	Obidio	5/32
16	Lionida	1/8	51	Vicente	5/32
17	Kayla	1/8	52	Julion	5/32
18	Antonio	1/8	53	Mercedes	5/32
19	Ignacio	5/32	54	Robinson	5/32
20	Carina	1/8	55	Celestiano	5/32
21	Paulina	1/8	56	Igl. Evangélica	5/32
22	Yolanda	5/32	57	Kike	5/32
23	Abraham	5/32	58	Pastora	5/32
24	Claribel	5/32	59	Georgina	7/32
25	Seferina	no disco	60	Jimi	1/4
26	Edita	1/4	61	Isidra	no disco
27	Carlos Espinosa	3/16	62	Pedro Morán	1/8
28	Pedro Espinosa	1/4	63	Darío Dominguez	1/8
29	Pablo	1/8	64	Hermelinda	1/8
30	Iglesia Adventista	5/32	65	Obelio	1/8
31	Demetrio	5/32	66	Berta	1/8
32	Yolis	5/32	67	Evausto	1/8
33	Domiciano	1/8	68	Fele	1/8
34	Yuni Castillo	1/8	69	Álvaro	1/8
35	Lucy Guerrel	1/8	70	Nerys	5/32



Numero	Dueño	Tamaño de Disco	Numero	Dueño	Tamaño de Disco
71	Ángel Rojas	1/4	79	Stevenson	5/32
72	Tano	5/32	80	Éufrates	5/32
73	Evangelina	5/32	81	Isabeth	5/32
74	Merien	5/32	82	Máximo	5/32
75	Leandro	5/32	83	Victor	3/16
76	Ana	5/32	84	Carlos	7/32
77	Leti	5/32	85	Fidel	7/32
78	Ofelina	no disco	86	Wilfredo	1/8

Guide for Sustainable Flow Reducer Projects 16

Appendix B: NeatWork Topography Input Tables for “As Is” and “All” Files

Table B1: Node Input Table to Create NeatWork “As Is” Topography File

T	0.00	0	0	0	0
N1	-4.01	0	0	0	1
N2	-2.62	0	0	0	1
N3	-24.59	0	0	0	1
N4	-26.14	0	0	0	1
N5	-27.71	0	0	0	1
N6	-27.53	0	0	0	1
N7	-27.38	0	0	0	1
N8	-28.35	0	0	0	1
N9	-32.49	0	0	0	1
N10	-36.12	0	0	0	1
N11	-47.12	0	0	0	1
N12	-46.23	0	0	0	1
N13	-46.13	0	0	0	1
N14	-45.67	0	0	0	1
N15	-45.34	0	0	0	1
N16	-37.11	0	0	0	1
N17	-33.78	0	0	0	1
N18	-27.25	0	0	0	1
N19	-26.09	0	0	0	1
N20	-45.72	0	0	0	1
N21	-36.68	0	0	0	1
N22	-31.90	0	0	0	1
N23	-46.15	0	0	0	1
N24	-46.71	0	0	0	1
N25	-27.89	0	0	0	1
N26	-27.89	0	0	0	1
N27	-33.58	0	0	0	1
N28	-36.88	0	0	0	1
N29	-38.35	0	0	0	1
N30	-38.86	0	0	0	1
N31	-37.13	0	0	0	1
N32	-49.48	0	0	0	1
N33	-29.26	0	0	0	1

Table B1: (Continued)

N34	-29.08	0	0	0	1
N35	-25.76	0	0	0	1
N36	-22.63	0	0	0	1
N37*	-30.94	0	0	0	1
N38	-22.68	0	0	0	1
N39	-23.88	0	0	0	1
N40	-17.68	0	0	0	1
N41	-22.96	0	0	0	1
N42	-20.78	0	0	0	1
N43	-39.22	0	0	0	1
N44	-40.41	0	0	0	1
N45	-55.37	0	0	0	1
N46	-48.29	0	0	0	1
N47	-47.60	0	0	0	1
N48	-48.34	0	0	0	1
N49	-52.65	0	0	0	1
N50	-54.48	0	0	0	1
N51	-51.26	0	0	0	1
N52	-51.46	0	0	0	1
N53	-50.09	0	0	0	1
N54	-49.86	0	0	0	1
N55	-49.66	0	0	0	1
N56	-40.11	0	0	0	1
N57	-48.87	0	0	0	1
N58	-48.62	0	0	0	1
N59	-53.06	0	0	0	1
N60	-40.98	0	0	0	1
N61	-38.98	0	0	0	1
N62	-35.88	0	0	0	1
N63	-36.94	0	0	0	1
N64	-33.74	0	0	0	1
N65	-33.54	0	0	0	1
N66	-33.16	0	0	0	1
N67	-31.71	0	0	0	1
N68	-30.54	0	0	0	1
N69	-33.62	0	0	0	1
N70	-34.91	0	0	0	1
N71	-36.64	0	0	0	1
N72	-35.39	0	0	0	1
N73	-32.47	0	0	0	1
N74	-31.23	0	0	0	1

Table B1: (Continued)

N75	-29.43	0	0	0	1
N76	-29.58	0	0	0	1
N77	-30.98	0	0	0	1
N78	-31.10	0	0	0	1
N79	-25.90	0	0	0	1
N80	-47.17	0	0	0	1
N81	-35.00	0	0	0	1
N82	-33.23	0	0	0	1
N83	-28.15	0	0	0	1
N84	-25.45	0	0	0	1
N85	-26.65	0	0	0	1
N86	-26.88	0	0	0	1
N87	-30.86	0	0	0	1
N88	-31.91	0	0	0	1
N89	-43.61	0	0	0	1
N90	-41.91	0	0	0	1
N91	-45.55	0	0	0	1
N92	-48.74	0	0	0	1
N93	-39.90	0	0	0	1
N94	-35.99	0	0	0	1
N95	-35.30	0	0	0	1
N96	-27.35	0	0	0	1
N97	-27.43	0	0	0	1
N1*	-45.80	0	0	0	1
N2*	-25.86	0	0	0	1
N3*	-20.35	0	0	0	1
N4*	-22.50	0	0	0	1
N6*	-41.68	0	0	0	1
N7*	-40.11	0	0	0	1
N8*	-38.23	0	0	0	1
N9*	-45.04	0	0	0	1
N5*	-48.29	0	0	0	2
P1	-27.79	0	0	1	2
P2	-29.34	0	0	1	2
P3	-32.92	0	0	1	2
P4	-32.44	0	0	1	2
P5	-36.12	0	0	1	2
P6	-46.36	0	0	1	2
P7	-46.10	0	0	1	2
P8	-43.92	0	0	1	2

Table B1: (Continued)

P9	-34.57	0	0	1	2
P10	-35.48	0	0	1	2
P11	-26.04	0	0	1	2
P12	-23.19	0	0	1	2
P13	-20.85	0	0	1	2
P14	-20.09	0	0	1	2
P15	-31.09	0	0	1	2
P16	-29.49	0	0	1	2
P17	-44.78	0	0	1	2
P18	-45.92	0	0	1	2
P19	-46.02	0	0	1	2
P20	-27.89	0	0	1	2
P21	-31.37	0	0	1	2
P22	-35.53	0	0	1	2
P23	-29.87	0	0	1	2
P24	-22.38	0	0	1	2
P25	-23.06	0	0	1	2
P26	-17.32	0	0	1	2
P27	-19.05	0	0	1	2
P28	-18.01	0	0	1	2
P29	-19.81	0	0	1	2
P30	-48.31	0	0	1	2
P31	-48.62	0	0	1	2
P32	-40.98	0	0	1	2
P33	-38.57	0	0	1	2
P34	-36.74	0	0	1	2
P35	-34.58	0	0	1	2
P36	-34.23	0	0	1	2
P37	-30.24	0	0	1	2
P38	-35.70	0	0	1	2
P39	-35.29	0	0	1	2
P40	-36.79	0	0	1	2
P41	-33.69	0	0	1	2
P42	-39.03	0	0	1	2
P43	-31.92	0	0	1	2
P44	-25.18	0	0	1	2
P45	-22.21	0	0	1	2
P46	-47.45	0	0	1	2
P47	-48.34	0	0	1	2
P48	-48.36	0	0	1	2

Table B1: (Continued)

P49	-49.25	0	0	1	2
P50	-40.49	0	0	1	2
P51	-17.07	0	0	1	2
P52	-25.40	0	0	1	2
P53	-26.52	0	0	1	2
P54	-31.30	0	0	1	2
P55	-30.81	0	0	1	2
P56	-15.47	0	0	1	2
P57	-36.38	0	0	1	2
P58	-42.23	0	0	1	2
P59	-44.15	0	0	1	2
P60	-27.48	0	0	1	2

Table B2: Arc Length Input Table to Create Neatwork "As Is" Topography File

T	N1	14.85
N1	N2	17.20
N2	N3	93.54
N3	N4	12.20
N4	N5	24.40
N5	N6	11.60
N6	N7	6.70
N7	N8	22.10
N8	N9	42.70
N9	N10	25.77
N10	N11	100.76
N11	N12	48.80
N12	N13	12.20
N13	N14	15.00
N14	N15	6.10
N15	N16	38.92
N16	N17	21.49
N17	N18	30.50
N18	N19	18.30
N12	N20	37.48
N20	N21	30.01
N21	N22	23.38
N12	N23	32.61
N23	N24	33.85
N8	N25	12.20

Table B2: (Continued)

N25	N26	33.43
N26	N27	48.80
N27	N28	5.00
N28	N29	42.85
N29	N30	4.50
N30	N31	7.80
N31	N32	34.08
N32	N33	59.35
N33	N34	6.10
N34	N35	20.70
N35	N36	35.90
N36	N37*	36.25
N36	N38	1.55
N38	N39	10.07
N39	N40	103.24
N35	N41	48.80
N41	N42	42.70
N30	N43	2.30
N43	N44	18.30
N44	N45	16.08
N45	N46	37.20
N46	N47	30.50
N47	N48	40.00
N48	N49	50.00
N49	N50	4.20
N50	N51	139.00
N51	N52	21.35
N52	N53	18.30
N53	N54	18.30
N54	N55	6.10
N55	N56	79.85
N46	N57	12.20
N57	N58	18.70
N58	N59	49.10
N59	N60	52.55
N60	N61	21.35
N61	N62	29.95
N62	N63	8.53
N62	N64	35.75
N64	N65	7.10

Table B2: (Continued)

N65	N66	47.80
N66	N67	24.40
N67	N68	42.70
N68	N69	46.79
N69	N70	24.40
N70	N71	36.60
N71	N72	36.60
N72	N73	26.22
N73	N74	24.40
N74	N75	24.40
N75	N76	6.10
N76	N77	6.10
N77	N78	2.70
N77	N79	72.02
N52	N80	61.80
N80	N81	42.64
N81	N82	12.00
N82	N83	30.00
N83	N84	23.50
N84	N85	20.60
N85	N86	3.90
N86	N87	29.69
N87	N88	6.00
N88	N89	68.99
N89	N90	7.00
N90	N91	35.68
N91	N92	20.00
N92	N93	47.97
N93	N94	37.87
N94	N95	6.00
N95	N96	47.48
N96	N97	18.00
N11	N1*	2.14
N18	N2*	6.10
N2*	N3*	27.98
N39	N4*	22.45
N57	N5*	6.10
N88	N6*	65.50
N91	N7*	10.95
N7*	N8*	24.00

Table B2: (Continued)

N92	N9*	8.00
N3	P1	19.37
N5	P2	9.63
N6	P3	145.67
N9	P4	18.30
N10	P5	0.50
N1*	P6	8.64
N13	P7	11.80
N14	P8	19.83
N16	P9	17.25
N17	P10	34.30
N19	P11	12.20
N19	P12	36.60
N3*	P13	6.10
N22	P14	55.00
N22	P15	2.70
N22	P16	26.88
N23	P17	18.30
N24	P18	18.30
N24	P19	14.87
N26	P20	0.80
N37*	P21	2.50
N37*	P22	35.53
N34	P23	30.50
N38	P24	4.78
N4*	P25	31.75
N40	P26	0.50
N40	P27	35.50
N42	P28	42.70
N42	P29	20.85
N57	P30	24.87
N58	P31	0.50
N60	P32	0.50
N62	P33	64.58
N63	P34	4.50
N64	P35	13.00
N66	P36	26.27
N67	P37	35.90
N69	P38	28.70
N70	P39	6.10

Table B2: (Continued)

N72	P40	50.84
N73	P41	11.00
N74	P42	72.92
N78	P43	4.80
N78	P44	17.31
N79	P45	23.00
N72	P46	14.20
N48	P47	6.90
N48	P48	7.53
N55	P49	12.20
N56	P50	8.00
N81	P51	66.74
N84	P52	6.00
N85	P53	1.20
N86	P54	14.60
N87	P55	3.00
N6*	P56	153.75
N89	P57	45.88
N8*	P58	30.00
N9*	P59	58.76
N97	P60	6.00

Table B3: Node Input Table to Create Neatwork "All" Topography File

T	0.00	0	0	0	0
N1	-4.01	0	0	0	1
N2	-2.62	0	0	0	1
N3	-24.59	0	0	0	1
N4	-26.14	0	0	0	1
N5	-27.71	0	0	0	1
N6	-27.53	0	0	0	1
N7	-27.38	0	0	0	1
N8	-28.35	0	0	0	1
N9	-32.49	0	0	0	1
N10	-36.12	0	0	0	1
N11	-47.12	0	0	0	1
N12	-46.23	0	0	0	1
N13	-46.13	0	0	0	1
N14	-45.67	0	0	0	1
N15	-45.34	0	0	0	1
N16	-37.11	0	0	0	1

Table B3: (Continued)

N17	-33.78	0	0	0	1
N18	-27.25	0	0	0	1
N19	-26.09	0	0	0	1
N20	-45.72	0	0	0	1
N21	-36.68	0	0	0	1
N22	-31.90	0	0	0	1
N23	-46.15	0	0	0	1
N24	-46.71	0	0	0	1
N25	-27.89	0	0	0	1
N26	-27.89	0	0	0	1
N27	-33.58	0	0	0	1
N28	-36.88	0	0	0	1
N29	-38.35	0	0	0	1
N30	-38.86	0	0	0	1
N31	-37.13	0	0	0	1
N32	-49.48	0	0	0	1
N33	-29.26	0	0	0	1
N34	-29.08	0	0	0	1
N35	-25.76	0	0	0	1
N36	-22.63	0	0	0	1
N37*	-30.94	0	0	0	1
N38	-22.68	0	0	0	1
N39	-23.88	0	0	0	1
N40	-17.68	0	0	0	1
N41	-22.96	0	0	0	1
N42	-20.78	0	0	0	1
N43	-39.22	0	0	0	1
N44	-40.41	0	0	0	1
N45	-55.37	0	0	0	1
N46	-48.29	0	0	0	1
N47	-47.60	0	0	0	1
N48	-48.34	0	0	0	1
N49	-52.65	0	0	0	1
N50	-54.48	0	0	0	1
N51	-51.26	0	0	0	1
N52	-51.46	0	0	0	1
N53	-50.09	0	0	0	1
N54	-49.86	0	0	0	1
N55	-49.66	0	0	0	1
N56	-40.11	0	0	0	1

Table B3: (Continued)

N57	-48.87	0	0	0	1
N58	-48.62	0	0	0	1
N59	-53.06	0	0	0	1
N60	-40.98	0	0	0	1
N61	-38.98	0	0	0	1
N62	-35.88	0	0	0	1
N63	-36.94	0	0	0	1
N64	-33.74	0	0	0	1
N65	-33.54	0	0	0	1
N66	-33.16	0	0	0	1
N67	-31.71	0	0	0	1
N68	-30.54	0	0	0	1
N69	-33.62	0	0	0	1
N70	-34.91	0	0	0	1
N71	-36.64	0	0	0	1
N72	-35.39	0	0	0	1
N73	-32.47	0	0	0	1
N74	-31.23	0	0	0	1
N75	-29.43	0	0	0	1
N76	-29.58	0	0	0	1
N77	-30.98	0	0	0	1
N78	-31.10	0	0	0	1
N79	-25.90	0	0	0	1
N80	-47.17	0	0	0	1
N81	-35.00	0	0	0	1
N82	-33.23	0	0	0	1
N83	-28.15	0	0	0	1
N84	-25.45	0	0	0	1
N85	-26.65	0	0	0	1
N86	-26.88	0	0	0	1
N87	-30.86	0	0	0	1
N88	-31.91	0	0	0	1
N89	-43.61	0	0	0	1
N90	-41.91	0	0	0	1
N91	-45.55	0	0	0	1
N92	-48.74	0	0	0	1
N93	-39.90	0	0	0	1
N94	-35.99	0	0	0	1
N95	-35.30	0	0	0	1
N96	-27.35	0	0	0	1

Table B3: (Continued)

N97	-27.43	0	0	0	1
N1*	-45.80	0	0	0	1
N2*	-25.86	0	0	0	1
N3*	-20.35	0	0	0	1
N4*	-22.50	0	0	0	1
N6*	-41.68	0	0	0	1
N7*	-40.11	0	0	0	1
N8*	-38.23	0	0	0	1
N9*	-45.04	0	0	0	1
N5*	-48.29	0	0	0	2
P1	-27.79	0	0	1	2
PN1	-29.79	0	0	1	2
P2	-29.34	0	0	1	2
P3	-32.92	0	0	1	2
P4	-32.44	0	0	1	2
P5	-36.12	0	0	1	2
P6	-46.36	0	0	1	2
P7	-46.10	0	0	1	2
P8	-43.92	0	0	1	2
P9	-34.57	0	0	1	2
P10	-35.48	0	0	1	2
P11	-26.04	0	0	1	2
P12	-23.19	0	0	1	2
P13	-20.85	0	0	1	2
P14	-20.09	0	0	1	2
P15	-31.09	0	0	1	2
P16	-29.49	0	0	1	2
P17	-44.78	0	0	1	2
P18	-45.92	0	0	1	2
P19	-46.02	0	0	1	2
PN2	-47.68	0	0	1	2
P20	-27.89	0	0	1	2
PN3	-35.94	0	0	1	2
P21	-31.37	0	0	1	2
P22	-35.53	0	0	1	2
P23	-29.87	0	0	1	2
P24	-22.38	0	0	1	2
P25	-23.06	0	0	1	2
P26	-17.32	0	0	1	2
P27	-19.05	0	0	1	2
PN4	-23.80	0	0	1	2

Table B3: (Continued)

P28	-18.01	0	0	1	2
P29	-19.81	0	0	1	2
P30	-48.31	0	0	1	2
P31	-48.62	0	0	1	2
P32	-40.98	0	0	1	2
P33	-38.57	0	0	1	2
P34	-36.74	0	0	1	2
P35	-34.58	0	0	1	2
P36	-34.23	0	0	1	2
P37	-30.24	0	0	1	2
PN5	-30.24	0	0	1	2
P38	-35.70	0	0	1	2
P39	-35.29	0	0	1	2
P40	-36.79	0	0	1	2
P41	-33.69	0	0	1	2
P42	-39.03	0	0	1	2
P43	-31.92	0	0	1	2
P44	-25.18	0	0	1	2
P45	-22.21	0	0	1	2
PN6	-25.64	0	0	1	2
P46	-47.45	0	0	1	2
P47	-48.34	0	0	1	2
P48	-48.36	0	0	1	2
PN7	-50.09	0	0	1	2
PN8	-49.79	0	0	1	2
P49	-49.25	0	0	1	2
P50	-40.49	0	0	1	2
P51	-17.07	0	0	1	2
PN9	-33.84	0	0	1	2
PN10	-24.69	0	0	1	2
P52	-25.40	0	0	1	2
P53	-26.52	0	0	1	2
P54	-31.30	0	0	1	2
P55	-30.81	0	0	1	2
P56	-15.47	0	0	1	2
P57	-36.38	0	0	1	2
P58	-42.23	0	0	1	2
P59	-44.15	0	0	1	2
PN11	-40.43	0	0	1	2
PN12	-28.88	0	0	1	2

Table B3: (Continued)

P60	-27.48	0	0	1	2
PN13	-27.56	0	0	1	2

Table B4: Arc Length Input Table to Create Neatwork “All” Topography File

T	N1	14.85
N1	N2	17.20
N2	N3	93.54
N3	N4	12.20
N4	N5	24.40
N5	N6	11.60
N6	N7	6.70
N7	N8	22.10
N8	N9	42.70
N9	N10	25.77
N10	N11	100.76
N11	N12	48.80
N12	N13	12.20
N13	N14	15.00
N14	N15	6.10
N15	N16	38.92
N16	N17	21.49
N17	N18	30.50
N18	N19	18.30
N12	N20	37.48
N20	N21	30.01
N21	N22	23.38
N12	N23	32.61
N23	N24	33.85
N8	N25	12.20
N25	N26	33.43
N26	N27	48.80
N27	N28	5.00
N28	N29	42.85
N29	N30	4.50
N30	N31	7.80
N31	N32	34.08
N32	N33	59.35
N33	N34	6.10
N34	N35	20.70

Table B4: (Continued)

N35	N36	35.90
N36	N37*	36.25
N36	N38	1.55
N38	N39	10.07
N39	N40	103.24
N35	N41	48.80
N29	N30	4.50
N30	N31	7.80
N31	N32	34.08
N32	N33	59.35
N33	N34	6.10
N34	N35	20.70
N35	N36	35.90
N36	N37*	36.25
N36	N38	1.55
N38	N39	10.07
N39	N40	103.24
N35	N41	48.80
N41	N42	42.70
N30	N43	2.30
N43	N44	18.30
N44	N45	16.08
N45	N46	37.20
N46	N47	30.50
N47	N48	40.00
N48	N49	50.00
N49	N50	4.20
N50	N51	139.00
N51	N52	21.35
N52	N53	18.30
N53	N54	18.30
N54	N55	6.10
N55	N56	79.85
N46	N57	12.20
N57	N58	18.70
N58	N59	49.10
N59	N60	52.55
N60	N61	21.35
N61	N62	29.95
N62	N63	8.53

Table B4: (Continued)

N62	N64	35.75
N64	N65	7.10
N65	N66	47.80
N66	N67	24.40
N67	N68	42.70
N68	N69	46.79
N69	N70	24.40
N70	N71	36.60
N71	N72	36.60
N72	N73	26.22
N73	N74	24.40
N74	N75	24.40
N75	N76	6.10
N76	N77	6.10
N77	N78	2.70
N77	N79	72.02
N52	N80	61.80
N80	N81	42.64
N81	N82	12.00
N82	N83	30.00
N83	N84	23.50
N84	N85	20.60
N85	N86	3.90
N86	N87	29.69
N87	N88	6.00
N88	N89	68.99
N89	N90	7.00
N90	N91	35.68
N91	N92	20.00
N92	N93	47.97
N93	N94	37.87
N94	N95	6.00
N95	N96	47.48
N96	N97	18.00
N11	N1*	2.14
N18	N2*	6.10
N2*	N3*	27.98
N39	N4*	22.45
N57	N5*	6.10
N88	N6*	65.50

Table B4: (Continued)

N91	N7*	10.95
N7*	N8*	24.00
N92	N9*	8.00
N3	P1	19.37
N5	P2	9.63
N6	P3	145.67
N9	P4	18.30
N10	P5	0.50
N1*	P6	8.64
N13	P7	11.80
N14	P8	19.83
N16	P9	17.25
N17	P10	34.30
N19	P11	12.20
N19	P12	36.60
N3*	P13	6.10
N22	P14	55.00
N22	P15	2.70
N22	P16	26.88
N23	P17	18.30
N24	P18	18.30
N24	P19	14.87
N26	P20	0.80
N37*	P21	2.50
N37*	P22	35.53
N34	P23	30.50
N38	P24	4.78
N4*	P25	31.75
N40	P26	0.50
N40	P27	35.50
N42	P28	42.70
N42	P29	20.85
N57	P30	24.87
N58	P31	0.50
N60	P32	0.50
N62	P33	64.58
N63	P34	4.50
N64	P35	13.00
N66	P36	26.27

Table B4: (Continued)

N67	P37	35.90
N69	P38	28.70
N70	P39	6.10
N72	P40	50.84
N73	P41	11.00
N74	P42	72.92
N78	P43	4.80
N78	P44	17.31
N79	P45	23.00
N72	P46	14.20
N48	P47	6.90
N48	P48	7.53
N55	P49	12.20
N56	P50	8.00
N81	P51	66.74
N84	P52	6.00
N85	P53	1.20
N86	P54	14.60
N87	P55	3.00
N6*	P56	153.75
N89	P57	45.88
N8*	P58	30.00
N9*	P59	58.76
N97	P60	6.00

Appendix C: NeatWork Simulation Results

Table C1: NeatWork Simulation Results for "All" Design File

Faucet Idea	No. of Occurrences	Min Flow (L/s)	Average Flow (L/s)	Max Flow (L/s)	Variability (%)	Flow <0.1 L/s (%)	Flow <0.3 L/s (%)	No. of Failures
Global average			0.2037			0.53	0.97	2
P1	48	0.2137	0.2142	0.215	0.15	0	0	0
P10	44	0.1596	0.184	0.2173	8.28	0	0	0
P11	34	0.1528	0.2071	0.2743	16.08	0	0	0
P12	38	0.097	0.1795	0.2987	26.64	2.63	0	0
P13	39	0.0723	0.2084	0.3538	33.02	2.56	7.69	0
P14	37	0.0818	0.2012	0.3357	31.33	2.7	8.11	0
P15	40	0.1997	0.2297	0.2815	8.34	0	0	0
P16	47	0.1764	0.2118	0.2627	10.32	0	0	0
P17	37	0.1725	0.2114	0.2518	8.5	0	0	0
P18	38	0.1424	0.203	0.2451	12.92	0	0	0
P19	37	0.1436	0.198	0.2442	12.34	0	0	0
P2	36	0.22	0.2206	0.2213	0.18	0	0	0
P20	33	0.2111	0.2123	0.214	0.28	0	0	0
P21	32	0.1889	0.2198	0.266	9.99	0	0	0
P22	43	0.1574	0.1819	0.2187	8.37	0	0	0
P23	46	0.166	0.1814	0.206	6.22	0	0	0
P24	39	0.1777	0.2204	0.2862	11.77	0	0	0
P25	46	0.1615	0.2034	0.2743	14.89	0	0	0
P26	49	0.0558	0.1958	0.3511	39.6	12.24	14.29	0
P27	48	0.14	0.1978	0.3213	22.82	0	2.08	0
P28	41	0.1114	0.204	0.3011	25.62	0	2.44	0
P29	35	0.1442	0.195	0.2984	18.18	0	0	0
P3	39	0.2052	0.2057	0.2068	0.17	0	0	0
P30	37	0.181	0.1827	0.1847	0.5	0	0	0
P31	42	0.1818	0.1845	0.1882	0.65	0	0	0
P32	47	0.2322	0.2439	0.2587	2.21	0	0	0
P33	33	0.2009	0.2159	0.2341	3.38	0	0	0

Table C1: (Continued)

P34	47	0.2039	0.2183	0.2306	2.65	0	0	0
P35	43	0.1903	0.2068	0.2213	3.33	0	0	0
P36	41	0.1813	0.2027	0.2228	4.44	0	0	0
P37	39	0.1632	0.1802	0.2041	5.05	0	0	0
P38	44	0.1814	0.2012	0.2278	4.34	0	0	0
P39	39	0.1787	0.1984	0.2146	5.07	0	0	0
P4	47	0.2216	0.2244	0.2271	0.58	0	0	0
P40	35	0.1602	0.183	0.2158	7.17	0	0	0
P41	39	0.1965	0.2288	0.2649	8.1	0	0	0
P42	35	0.1617	0.1814	0.2271	7.96	0	0	0
P43	37	0.1748	0.2066	0.2469	8.73	0	0	0
P44	37	0.1213	0.2007	0.3015	23.93	0	2.7	0
P45	42	0.0	0.22	0.3659	39.11	4.76	21.43	2
P46	35	0.2178	0.2335	0.2631	4.67	0	0	0
P47	44	0.1816	0.1836	0.1857	0.54	0	0	0
P48	40	0.1816	0.1835	0.1859	0.56	0	0	0
P49	36	0.1498	0.1685	0.1806	5.22	0	0	0
P5	45	0.2374	0.2411	0.2458	0.81	0	0	0
P50	36	0.1734	0.2002	0.2198	6.15	0	0	0
P51	35	0.1335	0.1799	0.2194	9.45	0	0	0
P52	44	0.1886	0.2181	0.2451	5.92	0	0	0
P53	52	0.1973	0.2271	0.2557	5.1	0	0	0
P54	53	0.169	0.1878	0.2065	3.95	0	0	0
P55	40	0.167	0.1863	0.2044	4.22	0	0	0
P56	40	0.0535	0.2001	0.2694	24.43	2.5	0	0
P57	39	0.1655	0.1936	0.2202	5.73	0	0	0
P58	42	0.18	0.207	0.2318	5.35	0	0	0
P59	44	0.1854	0.2128	0.2348	5.38	0	0	0
P6	37	0.1666	0.1725	0.1805	1.99	0	0	0
P60	39	0.0865	0.2002	0.2931	29.1	10.26	0	0
P7	44	0.2203	0.2383	0.2655	4.53	0	0	0
P8	37	0.2072	0.2257	0.2564	4.8	0	0	0
P9	38	0.1584	0.1868	0.2201	8.51	0	0	0
PN1	46	0.2227	0.2232	0.2242	0.16	0	0	0
PN10	35	0.1852	0.2108	0.2353	5.63	0	0	0
PN11	32	0.1752	0.2043	0.2428	6.86	0	0	0
PN12	47	0.1403	0.221	0.284	14.69	0	0	0
PN13	31	0.1084	0.2099	0.3316	28.56	0	6.45	0

Table C1: (Continued)

PN3	42	0.2385	0.2398	0.2416	0.27	0	0	0
PN2	43	0.1469	0.1983	0.2491	11.39	0	0	0
PN4	35	0.1629	0.1943	0.2426	10.18	0	0	0
PN5	34	0.1569	0.1781	0.1976	5.18	0	0	0
PN6	48	0.1422	0.219	0.3215	19.88	0	4.17	0
PN7	45	0.1651	0.1762	0.1873	2.98	0	0	0
PN8	44	0.153	0.1711	0.1817	4.36	0	0	0
PN9	45	0.195	0.2061	0.2209	2.53	0	0	0

Table C2: NeatWork Simulation Results from "As Is" Design File

Faucet Idea	No. of Occurrences	Min Flow (L/s)	Average Flow (L/s)	Max Flow (L/s)	Variability (%)	Flow <0.1 L/s (%)	Flow <0.3 L/s (%)	No. of Failures
Global average			0.2014			1.16	0.56	8
P1	30	0.2161	0.2166	0.2174	0.14	0.0	0.0	0
P10	45	0.1488	0.184	0.2253	9.0	0.0	0.0	0
P11	41	0.1392	0.2067	0.2939	19.03	0.0	0.0	0
P12	39	0.0528	0.1815	0.3123	30.8	7.69	2.56	0
P13	42	0.0	0.1867	0.3287	44.12	11.9	4.76	3
P14	32	0.0	0.1919	0.3198	37.99	9.38	3.12	1
P15	29	0.1774	0.2289	0.2885	11.72	0.0	0.0	0
P16	43	0.153	0.2143	0.2711	13.0	0.0	0.0	0
P17	38	0.1821	0.2169	0.2478	7.33	0.0	0.0	0
P18	37	0.167	0.2104	0.2432	8.17	0.0	0.0	0
P19	44	0.1682	0.2163	0.2517	8.67	0.0	0.0	0
P2	52	0.223	0.2237	0.2247	0.17	0.0	0.0	0
P20	34	0.2159	0.2167	0.2184	0.26	0.0	0.0	0
P21	43	0.1448	0.1754	0.2122	9.3	0.0	0.0	0
P22	38	0.1632	0.1886	0.2229	7.53	0.0	0.0	0
P23	38	0.1691	0.1837	0.2034	5.33	0.0	0.0	0
P24	39	0.1446	0.1905	0.2447	13.14	0.0	0.0	0
P25	51	0.1653	0.2101	0.2608	11.27	0.0	0.0	0
P26	32	0.0636	0.2072	0.3549	33.31	6.25	9.38	0
P27	35	0.1366	0.2051	0.2993	22.28	0.0	0.0	0
P28	51	0.127	0.2095	0.3251	23.84	0.0	3.92	0
P29	43	0.1527	0.2055	0.2769	17.64	0.0	0.0	0

Table C2: (Continued)

P3	44	0.2079	0.2085	0.2096	0.17	0.0	0.0	0
P30	43	0.1781	0.1808	0.1846	0.72	0.0	0.0	0
P31	36	0.1796	0.183	0.1879	0.88	0.0	0.0	0
P32	42	0.2337	0.2426	0.2546	1.91	0.0	0.0	0
P33	37	0.2044	0.2156	0.2292	2.81	0.0	0.0	0
P34	40	0.2077	0.2193	0.2338	2.62	0.0	0.0	0
P35	41	0.1956	0.2082	0.2227	3.05	0.0	0.0	0
P36	50	0.1885	0.2021	0.2166	3.24	0.0	0.0	0
P37	42	0.167	0.1805	0.2016	4.68	0.0	0.0	0
P38	46	0.1765	0.1925	0.2176	4.85	0.0	0.0	0
P39	35	0.1745	0.191	0.2142	5.51	0.0	0.0	0
P4	40	0.2261	0.2286	0.2318	0.52	0.0	0.0	0
P40	37	0.1529	0.1814	0.2216	9.45	0.0	0.0	0
P41	47	0.1853	0.2247	0.2818	10.09	0.0	0.0	0
P42	43	0.1554	0.1791	0.2124	7.56	0.0	0.0	0
P43	44	0.1629	0.2037	0.2769	11.9	0.0	0.0	0
P44	37	0.0818	0.1777	0.2634	20.49	2.7	0.0	0
P45	44	0.0	0.1781	0.3361	51.55	20.45	9.09	3
P46	47	0.2111	0.2298	0.2558	4.5	0.0	0.0	0
P47	51	0.1771	0.1807	0.186	1.06	0.0	0.0	0
P48	41	0.1771	0.1809	0.1868	1.26	0.0	0.0	0
P49	39	0.1559	0.1686	0.1857	4.16	0.0	0.0	0
P5	41	0.2415	0.2451	0.2494	0.6	0.0	0.0	0
P50	37	0.1838	0.2024	0.2208	4.83	0.0	0.0	0
P51	41	0.1315	0.2046	0.2849	16.95	0.0	0.0	0
P52	42	0.1855	0.2118	0.249	7.73	0.0	0.0	0
P53	43	0.1978	0.225	0.2653	7.04	0.0	0.0	0
P54	39	0.1685	0.1862	0.2111	5.82	0.0	0.0	0
P55	37	0.1675	0.1843	0.2033	5.34	0.0	0.0	0
P56	44	0.0	0.187	0.3358	38.19	13.64	2.27	1
P57	42	0.1779	0.1962	0.2221	5.97	0.0	0.0	0
P58	46	0.1842	0.2069	0.237	5.88	0.0	0.0	0
P59	44	0.1832	0.2081	0.2362	6.89	0.0	0.0	0
P6	40	0.1601	0.1721	0.1845	3.18	0.0	0.0	0
P60	35	0.1244	0.1939	0.2668	18.06	0.0	0.0	0
P7	32	0.2105	0.24	0.2619	5.04	0.0	0.0	0
P8	49	0.1974	0.2286	0.2581	5.76	0.0	0.0	0
P9	40	0.1468	0.1811	0.2159	8.14	0.0	0.0	0

Table C3: NeatWork Simulation Results for "All As Is Sizes" Design File

Faucet Idea	No. of Occurrences	Min Flow (L/s)	Average Flow (L/s)	Max Flow (L/s)	Variability (%)	Flow <0.1 L/s (%)	Flow <0.3 L/s (%)	No. of Failures
Global average			0.1867			4.23	0.2	26
P1	44	0.2145	0.2154	0.2162	0.21	0.0	0.0	0
P10	40	0.1589	0.1849	0.2164	7.9	0.0	0.0	0
P11	40	0.1471	0.1979	0.2631	14.85	0.0	0.0	0
P12	37	0.0865	0.1835	0.3115	26.68	2.7	2.7	0
P13	35	0.0421	0.2002	0.3516	36.75	5.71	2.86	0
P14	29	0.0469	0.1775	0.2994	33.11	10.34	0.0	0
P15	46	0.1969	0.2333	0.2772	8.65	0.0	0.0	0
P16	38	0.1734	0.212	0.2579	9.89	0.0	0.0	0
P17	33	0.1761	0.2125	0.2474	7.91	0.0	0.0	0
P18	31	0.1566	0.1991	0.2411	10.59	0.0	0.0	0
P19	43	0.1578	0.206	0.2552	11.79	0.0	0.0	0
P2	40	0.221	0.2221	0.2238	0.28	0.0	0.0	0
P20	43	0.2131	0.2145	0.2167	0.36	0.0	0.0	0
P21	39	0.1453	0.1753	0.2092	9.43	0.0	0.0	0
P22	39	0.1636	0.186	0.2119	6.48	0.0	0.0	0
P23	43	0.1647	0.1806	0.2066	5.01	0.0	0.0	0
P24	40	0.1759	0.2269	0.2761	11.49	0.0	0.0	0
P25	37	0.1598	0.2015	0.2471	10.36	0.0	0.0	0
P26	40	0.016	0.1747	0.3099	41.52	15.0	5.0	0
P27	41	0.1244	0.1858	0.2886	20.42	0.0	0.0	0
P28	39	0.1132	0.1948	0.2564	18.88	0.0	0.0	0
P29	35	0.1451	0.2098	0.2692	15.56	0.0	0.0	0
P3	44	0.2062	0.2071	0.2086	0.27	0.0	0.0	0
P30	38	0.1756	0.1784	0.1808	0.71	0.0	0.0	0
P31	41	0.1774	0.1802	0.1846	0.83	0.0	0.0	0
P32	42	0.2305	0.2376	0.2474	1.69	0.0	0.0	0
P33	36	0.1998	0.2089	0.2205	2.52	0.0	0.0	0
P34	35	0.2027	0.2135	0.2291	2.94	0.0	0.0	0
P35	40	0.1916	0.2017	0.2153	2.82	0.0	0.0	0
P36	41	0.1802	0.1945	0.2127	3.81	0.0	0.0	0
P37	45	0.1559	0.1717	0.186	3.99	0.0	0.0	0
P38	44	0.1665	0.1835	0.2045	5.54	0.0	0.0	0
P39	42	0.1631	0.1822	0.2099	5.64	0.0	0.0	0

Table C3: (Continued)

P4	46	0.2236	0.2265	0.2294	0.61	0.0	0.0	0
P40	41	0.1489	0.1719	0.2082	7.66	0.0	0.0	0
P41	33	0.175	0.2046	0.2524	8.19	0.0	0.0	0
P42	39	0.1498	0.175	0.2016	7.0	0.0	0.0	0
P43	40	0.1524	0.193	0.2699	11.51	0.0	0.0	0
P44	42	0.0161	0.1674	0.2731	30.72	7.14	0.0	0
P45	48	0.0	0.1265	0.4067	82.77	43.75	4.17	10
P46	45	0.2061	0.2241	0.2458	4.9	0.0	0.0	0
P47	51	0.173	0.1767	0.1798	0.8	0.0	0.0	0
P48	36	0.173	0.1766	0.1799	0.93	0.0	0.0	0
P49	42	0.1376	0.1563	0.1682	5.5	0.0	0.0	0
P5	39	0.2396	0.2429	0.2474	0.66	0.0	0.0	0
P50	43	0.1522	0.1828	0.2074	7.9	0.0	0.0	0
P51	38	0.0	0.1299	0.2136	40.99	28.95	0.0	1
P52	35	0.1418	0.1845	0.2166	8.35	0.0	0.0	0
P53	42	0.1747	0.1968	0.2273	6.89	0.0	0.0	0
P54	41	0.1443	0.1699	0.1866	5.31	0.0	0.0	0
P55	44	0.1422	0.168	0.1884	5.66	0.0	0.0	0
P56	47	0.0	0.0744	0.1801	84.92	55.32	0.0	14
P57	46	0.1588	0.1791	0.1974	4.63	0.0	0.0	0
P58	38	0.1746	0.1902	0.2143	5.21	0.0	0.0	0
P59	49	0.172	0.1905	0.2166	6.13	0.0	0.0	0
P6	46	0.1633	0.1711	0.1843	2.43	0.0	0.0	0
P60	33	0.0	0.0961	0.1999	47.98	57.58	0.0	1
P7	32	0.218	0.2355	0.2616	4.6	0.0	0.0	0
P8	45	0.2055	0.2264	0.2547	5.3	0.0	0.0	0
P9	36	0.1589	0.1868	0.2289	9.33	0.0	0.0	0
PN1	36	0.2235	0.2244	0.2257	0.21	0.0	0.0	0
PN10	45	0.1346	0.1807	0.2202	8.9	0.0	0.0	0
PN11	37	0.1506	0.1716	0.2052	7.85	0.0	0.0	0
PN12	38	0.0521	0.1128	0.2139	24.52	31.58	0.0	0
PN13	36	0.0153	0.0976	0.1997	50.6	61.11	0.0	0
PN2	29	0.1599	0.1988	0.2314	9.59	0.0	0.0	0
PN3	44	0.2407	0.2418	0.2434	0.26	0.0	0.0	0
PN4	40	0.1631	0.1955	0.2351	8.9	0.0	0.0	0
PN5	45	0.1512	0.1685	0.1949	4.83	0.0	0.0	0
PN6	40	0.0644	0.1823	0.2917	25.64	2.5	0.0	0
PN7	47	0.1519	0.1652	0.1755	3.6	0.0	0.0	0
PN8	49	0.1408	0.1591	0.1741	5.46	0.0	0.0	0
PN9	52	0.1655	0.1877	0.208	4.4	0.0	0.0	0

Table C4: NeatWork Simulation Results for “All As Is Sizes No Discs” Design File

Faucet Idea	No. of Occurrences	Min Flow (L/s)	Average Flow (L/s)	Max Flow (L/s)	Variability (%)	Flow <0.1 L/s (%)	Flow <0.3 L/s (%)	No. of Failures
Global average			0.2082			7.57	11.47	120
P1	39	0.2115	0.2141	0.2158	0.48	0.0	0.0	0
P10	38	0.1419	0.1791	0.2204	9.48	0.0	0.0	0
P11	40	0.1011	0.1991	0.2873	18.19	0.0	0.0	0
P12	40	0.0	0.1626	0.2695	29.52	2.5	0.0	1
P13	33	0.0	0.1663	0.3273	43.89	12.12	3.03	1
P14	48	0.0	0.1698	0.273	40.67	16.67	0.0	1
P15	39	0.1685	0.2263	0.2852	11.34	0.0	0.0	0
P16	35	0.1436	0.1997	0.2558	11.75	0.0	0.0	0
P17	46	0.1521	0.195	0.2481	13.41	0.0	0.0	0
P18	42	0.106	0.1753	0.233	22.79	0.0	0.0	0
P19	36	0.1073	0.1767	0.2427	23.42	0.0	0.0	0
P2	38	0.2173	0.2202	0.2225	0.59	0.0	0.0	0
P20	48	0.2077	0.2117	0.2144	0.84	0.0	0.0	0
P21	40	0.1397	0.1647	0.1876	7.85	0.0	0.0	0
P22	46	0.1589	0.1801	0.208	6.52	0.0	0.0	0
P23	35	0.1593	0.1721	0.1979	5.27	0.0	0.0	0
P24	47	0.1657	0.2096	0.2696	13.07	0.0	0.0	0
P25	41	0.152	0.1867	0.2529	12.28	0.0	0.0	0
P26	38	0.0	0.1541	0.3065	52.23	23.68	2.63	2
P27	37	0.1079	0.1709	0.2622	21.65	0.0	0.0	0
P28	48	0.0259	0.1579	0.2799	36.73	20.83	0.0	0
P3	44	0.2029	0.2053	0.2075	0.54	0.0	0.0	0
P30	43	0.1705	0.1746	0.1791	1.08	0.0	0.0	0
P31	45	0.1726	0.1767	0.1817	1.17	0.0	0.0	0
P32	45	0.2196	0.2311	0.2431	2.17	0.0	0.0	0
P33	36	0.189	0.2041	0.2162	3.32	0.0	0.0	0
P34	36	0.191	0.206	0.2226	3.17	0.0	0.0	0
P35	44	0.1771	0.1945	0.211	3.53	0.0	0.0	0
P36	43	0.1686	0.1883	0.2054	4.35	0.0	0.0	0
P37	34	0.1448	0.164	0.1794	5.26	0.0	0.0	0
P38	35	0.1528	0.1782	0.2011	6.34	0.0	0.0	0
P39	46	0.1491	0.1753	0.2017	6.67	0.0	0.0	0
P4	28	0.2206	0.2241	0.2272	0.7	0.0	0.0	0

Table C4: (Continued)

P40	46	0.1462	0.1664	0.1995	7.58	0.0	0.0	0
P41	36	0.1697	0.2019	0.2587	10.0	0.0	0.0	0
P42	40	0.1487	0.1699	0.1988	7.08	0.0	0.0	0
P43	47	0.1503	0.1815	0.2194	9.35	0.0	0.0	0
P44	42	0.0	0.1613	0.2689	33.49	9.52	0.0	1
P45	34	0.0	0.111	0.277	73.04	41.18	0.0	7
P46	29	0.2018	0.2164	0.2417	3.92	0.0	0.0	0
P47	42	0.1651	0.1719	0.1778	1.6	0.0	0.0	0
P48	45	0.1651	0.1722	0.1775	1.79	0.0	0.0	0
P49	44	0.0844	0.1221	0.1628	17.02	13.64	0.0	0
P5	44	0.2372	0.2412	0.2445	0.72	0.0	0.0	0
P50	55	0.0243	0.1357	0.2094	36.46	12.73	0.0	0
P51	39	0.0	0.0468	0.1899	121.72	82.05	0.0	18
P52	43	0.089	0.1529	0.2065	19.3	4.65	0.0	0
P53	34	0.1084	0.1662	0.2134	15.28	0.0	0.0	0
P54	36	0.1208	0.153	0.1811	9.46	0.0	0.0	0
P55	46	0.1186	0.1513	0.19	11.03	0.0	0.0	0
P56	46	0.0	0.0213	0.1696	212.01	91.3	0.0	34
P57	39	0.1447	0.1628	0.1894	7.01	0.0	0.0	0
P58	43	0.1445	0.1736	0.2102	9.03	0.0	0.0	0
P59	38	0.136	0.1695	0.2086	11.55	0.0	0.0	0
P6	39	0.1581	0.168	0.1796	2.78	0.0	0.0	0
P60	35	0.0	0.0408	0.1499	110.97	88.57	0.0	16
P7	37	0.2061	0.2318	0.2537	4.71	0.0	0.0	0
P8	39	0.1927	0.2205	0.243	4.75	0.0	0.0	0
P9	42	0.1397	0.1795	0.2155	9.24	0.0	0.0	0
PN1	39	0.6575	0.663	0.6674	0.42	0.0	100.0	0
PN2	39	0.2689	0.3542	0.4438	12.34	0.0	92.31	0
PN10	40	0.1652	0.2883	0.4191	21.94	0.0	37.5	0
PN11	47	0.2662	0.3461	0.4693	11.23	0.0	87.23	0
PN12	47	0.0	0.0794	0.2289	104.49	51.06	0.0	24
PN13	38	0.0	0.0547	0.1868	107.89	84.21	0.0	15
PN3	33	0.6986	0.7065	0.7127	0.49	0.0	100.0	0
PN4	42	0.326	0.3723	0.4532	7.0	0.0	100.0	0
PN5	45	0.3821	0.4356	0.5017	5.54	0.0	100.0	0
PN6	34	0.0761	0.2265	0.3947	32.94	2.94	11.76	0
PN7	43	0.5264	0.6173	0.7107	9.92	0.0	100.0	0
PN8	44	0.3908	0.5002	0.6085	13.86	0.0	100.0	0
PN9	38	0.1424	0.1667	0.2009	8.94	0.0	0.0	0

Table C5: NeatWork Simulation Results for “All As Is Sizes Discs 396” Design File

Faucet Idea	No. of Occurrences	Min Flow (L/s)	Average Flow (L/s)	Max Flow (L/s)	Variability (%)	Flow <0.1 L/s (%)	Flow <0.3 L/s (%)	No. of Failures
Global average			0.1852			6.57	0.27	20
P1	48	0.2146	0.2155	0.2166	0.2	0.0	0.0	0
P10	37	0.1539	0.1792	0.2167	6.73	0.0	0.0	0
P11	42	0.1421	0.2074	0.2919	16.54	0.0	0.0	0
P12	46	0.0767	0.178	0.271	21.35	4.35	0.0	0
P13	36	0.0405	0.183	0.3015	34.84	11.11	2.78	0
P14	47	0.0	0.1917	0.3478	34.53	8.51	2.13	1
P15	29	0.1953	0.2274	0.2763	8.03	0.0	0.0	0
P16	42	0.1705	0.2039	0.2545	9.1	0.0	0.0	0
P17	39	0.1693	0.2042	0.2631	10.28	0.0	0.0	0
P18	45	0.1398	0.1942	0.2399	12.48	0.0	0.0	0
P19	39	0.141	0.194	0.2519	13.9	0.0	0.0	0
P2	42	0.2212	0.2222	0.2234	0.25	0.0	0.0	0
P20	55	0.2136	0.2149	0.2167	0.33	0.0	0.0	0
P21	42	0.1411	0.1733	0.2011	8.84	0.0	0.0	0
P22	39	0.1601	0.1892	0.22	7.96	0.0	0.0	0
P23	37	0.1636	0.181	0.1981	5.14	0.0	0.0	0
P24	44	0.1715	0.2331	0.3006	13.37	0.0	2.27	0
P25	39	0.1568	0.2071	0.2562	12.67	0.0	0.0	0
P26	41	0.0252	0.1855	0.3228	39.24	12.2	7.32	0
P27	33	0.135	0.1907	0.3099	21.44	0.0	3.03	0
P28	36	0.0829	0.1867	0.2942	26.67	5.56	0.0	0
P29	36	0.1301	0.1954	0.2692	19.48	0.0	0.0	0
P30	44	0.1746	0.1787	0.1821	0.91	0.0	0.0	0
P31	41	0.1758	0.1805	0.1841	0.96	0.0	0.0	0
P32	40	0.2255	0.239	0.2492	1.77	0.0	0.0	0
P33	40	0.2037	0.213	0.2258	2.58	0.0	0.0	0
P34	41	0.1985	0.215	0.2296	2.85	0.0	0.0	0
P35	36	0.1849	0.2037	0.2201	3.32	0.0	0.0	0
P36	33	0.186	0.1973	0.2137	3.25	0.0	0.0	0
P37	45	0.1512	0.1749	0.1882	4.02	0.0	0.0	0
P38	45	0.1595	0.1865	0.2116	5.67	0.0	0.0	0
P39	42	0.1554	0.1864	0.2167	7.12	0.0	0.0	0

Table C5: (Continued)

P4	35	0.224	0.2264	0.2302	0.59	0.0	0.0	0
P40	39	0.145	0.1763	0.2068	10.12	0.0	0.0	0
P41	39	0.1855	0.2192	0.261	9.39	0.0	0.0	0
P42	35	0.1525	0.1732	0.2043	7.52	0.0	0.0	0
P43	38	0.1596	0.1994	0.2646	11.83	0.0	0.0	0
P44	39	0.0681	0.1786	0.3195	32.97	12.82	2.56	0
P45	34	0.0	0.0747	0.1487	54.9	73.53	0.0	4
P46	46	0.2051	0.2279	0.258	5.7	0.0	0.0	0
P47	38	0.174	0.1774	0.18	0.92	0.0	0.0	0
P48	44	0.1742	0.1774	0.1813	1.04	0.0	0.0	0
P49	41	0.1282	0.1568	0.1722	6.88	0.0	0.0	0
P5	46	0.24	0.2431	0.2485	0.72	0.0	0.0	0
P50	37	0.1351	0.1818	0.2078	9.17	0.0	0.0	0
P51	40	0.0	0.0661	0.1013	32.67	97.5	0.0	1
P52	43	0.1515	0.1879	0.2186	7.25	0.0	0.0	0
P53	45	0.164	0.2	0.2365	7.78	0.0	0.0	0
P54	50	0.1497	0.1723	0.1887	4.78	0.0	0.0	0
P55	54	0.1525	0.1707	0.1869	4.76	0.0	0.0	0
P56	42	0.0	0.0811	0.2131	86.08	52.38	0.0	13
P57	43	0.1643	0.1824	0.195	4.42	0.0	0.0	0
P58	29	0.1725	0.1898	0.215	5.46	0.0	0.0	0
P59	53	0.1705	0.1891	0.2081	4.63	0.0	0.0	0
P6	37	0.1636	0.1703	0.1796	2.14	0.0	0.0	0
P60	40	0.0	0.1066	0.2301	48.59	55.0	0.0	1
P7	40	0.2151	0.2387	0.2631	4.76	0.0	0.0	0
P8	46	0.202	0.2231	0.2478	4.62	0.0	0.0	0
P9	33	0.1522	0.1769	0.1995	6.78	0.0	0.0	0
PN1	40	0.2236	0.2245	0.2254	0.19	0.0	0.0	0
PN10	48	0.1062	0.1351	0.1522	7.91	0.0	0.0	0
PN11	33	0.1537	0.1666	0.1945	5.51	0.0	0.0	0
PN12	35	0.0474	0.085	0.1454	31.23	74.29	0.0	0
PN13	54	0.0097	0.1016	0.2306	49.24	53.7	0.0	0
PN2	39	0.1446	0.1907	0.2378	10.89	0.0	0.0	0
PN3	28	0.2409	0.2422	0.2438	0.28	0.0	0.0	0
PN4	41	0.1166	0.1465	0.1737	10.14	0.0	0.0	0
PN5	44	0.1453	0.1734	0.1935	5.55	0.0	0.0	0
PN6	36	0.0486	0.1104	0.1732	28.58	33.33	0.0	0
PN7	37	0.2192	0.249	0.2645	4.21	0.0	0.0	0
PN8	25	0.1981	0.2289	0.248	5.08	0.0	0.0	0
PN9	49	0.1697	0.1905	0.2087	4.07	0.0	0.0	0

Table C6: NeatWork Simulation Results for “All As Is Sizes Discs Closest” Design File

Faucet Idea	No. of Occurrences	Min Flow (L/s)	Average Flow (L/s)	Max Flow (L/s)	Variability (%)	Flow <0.1 L/s (%)	Flow <0.3 L/s (%)	No. of Failures
Global average			0.1881			4.87	3.13	45
P1	44	0.2144	0.2154	0.2164	0.2	0.0	0.0	0
P10	38	0.1596	0.1768	0.2037	6.79	0.0	0.0	0
P11	35	0.1562	0.2023	0.2747	16.8	0.0	0.0	0
P12	35	0.1027	0.1689	0.2947	26.38	0.0	0.0	0
P13	44	0.0319	0.1784	0.3573	40.86	13.64	4.55	0
P14	43	0.043	0.17	0.3029	34.38	9.3	2.33	0
P15	44	0.1914	0.227	0.2802	9.57	0.0	0.0	0
P16	44	0.1677	0.1994	0.2305	7.85	0.0	0.0	0
P17	36	0.1636	0.202	0.2333	8.8	0.0	0.0	0
P18	37	0.1352	0.1925	0.2403	15.02	0.0	0.0	0
P19	46	0.1364	0.1997	0.2516	14.85	0.0	0.0	0
P2	38	0.2207	0.2219	0.2231	0.25	0.0	0.0	0
P20	35	0.2129	0.2142	0.2154	0.29	0.0	0.0	0
P21	40	0.135	0.1646	0.1892	8.49	0.0	0.0	0
P22	40	0.1551	0.1808	0.2177	7.52	0.0	0.0	0
P23	41	0.1572	0.1757	0.1989	5.16	0.0	0.0	0
P25	50	0.1408	0.1949	0.2459	11.53	0.0	0.0	0
P26	37	0.0	0.1604	0.3463	50.03	16.22	5.41	2
P27	34	0.1203	0.1831	0.2965	22.19	0.0	0.0	0
P28	35	0.0686	0.1598	0.283	32.67	5.71	0.0	0
P29	42	0.1045	0.177	0.2384	17.88	0.0	0.0	0
P3	36	0.2055	0.2069	0.2082	0.24	0.0	0.0	0
P30	37	0.1751	0.1785	0.1818	0.88	0.0	0.0	0
P31	41	0.1765	0.1797	0.1831	0.81	0.0	0.0	0
P32	36	0.2292	0.2363	0.2431	1.64	0.0	0.0	0
P33	42	0.2002	0.2099	0.2158	1.84	0.0	0.0	0
P34	40	0.2032	0.2135	0.2236	2.43	0.0	0.0	0
P35	40	0.1905	0.2012	0.2151	2.7	0.0	0.0	0
P36	43	0.1828	0.1942	0.2071	3.23	0.0	0.0	0
P37	34	0.1595	0.1689	0.1826	3.52	0.0	0.0	0
P38	36	0.1619	0.1813	0.2056	5.28	0.0	0.0	0
P39	43	0.1548	0.1773	0.203	5.97	0.0	0.0	0
P4	37	0.2233	0.2264	0.2288	0.52	0.0	0.0	0

Table C6: (Continued)

P40	41	0.1362	0.1647	0.1948	7.57	0.0	0.0	0
P41	44	0.1601	0.2112	0.2637	10.84	0.0	0.0	0
P42	42	0.1423	0.1671	0.1951	7.63	0.0	0.0	0
P43	49	0.1381	0.1891	0.2557	13.1	0.0	0.0	0
P44	43	0.0	0.1446	0.2679	39.38	23.26	0.0	2
P45	45	0.0	0.1068	0.2723	86.41	53.33	0.0	12
P46	45	0.1984	0.2203	0.2483	4.9	0.0	0.0	0
P47	36	0.1722	0.1767	0.181	1.2	0.0	0.0	0
P48	43	0.1722	0.1767	0.1806	1.06	0.0	0.0	0
P49	47	0.1337	0.156	0.1748	6.4	0.0	0.0	0
P5	39	0.2391	0.2429	0.2474	0.65	0.0	0.0	0
P50	32	0.1451	0.1774	0.2068	8.99	0.0	0.0	0
P51	40	0.0	0.1191	0.2215	51.38	30.0	0.0	4
P52	40	0.137	0.1817	0.2465	11.4	0.0	0.0	0
P53	32	0.15	0.1923	0.2381	11.14	0.0	0.0	0
P54	35	0.1418	0.1643	0.1856	6.44	0.0	0.0	0
P55	35	0.1399	0.165	0.1852	6.79	0.0	0.0	0
P56	40	0.0	0.067	0.2213	109.8	60.0	0.0	17
P57	42	0.1634	0.1798	0.2054	5.71	0.0	0.0	0
P58	45	0.1714	0.1876	0.2092	4.72	0.0	0.0	0
P59	46	0.1685	0.1876	0.2248	6.29	0.0	0.0	0
P6	36	0.1621	0.1701	0.1816	2.56	0.0	0.0	0
P60	43	0.0	0.0918	0.2202	70.58	60.47	0.0	5
P7	41	0.2189	0.238	0.2691	5.24	0.0	0.0	0
P8	41	0.2072	0.2205	0.2395	3.99	0.0	0.0	0
P9	51	0.1586	0.1792	0.2128	7.21	0.0	0.0	0
PN1	36	0.2229	0.2242	0.2254	0.24	0.0	0.0	0
PN10	40	0.2861	0.3652	0.4144	8.37	0.0	95.0	0
PN11	49	0.1474	0.1647	0.1928	5.5	0.0	0.0	0
PN12	35	0.0407	0.1371	0.262	32.88	14.29	0.0	0
PN13	41	0.0	0.0815	0.1941	63.8	63.41	0.0	2
PN2	39	0.1404	0.1945	0.2404	13.96	0.0	0.0	0
PN3	37	0.2395	0.2418	0.2442	0.37	0.0	0.0	0
PN4	45	0.316	0.3935	0.4748	9.2	0.0	100.0	0
PN5	41	0.1552	0.1692	0.1836	4.72	0.0	0.0	0
PN6	46	0.0	0.2248	0.3562	29.73	2.17	10.87	1
PN7	43	0.1476	0.1646	0.1798	4.18	0.0	0.0	0
PN8	49	0.1368	0.1582	0.1763	6.0	0.0	0.0	0
PN9	44	0.1641	0.1854	0.2128	5.11	0.0	0.0	0

Appendix D: NeatWork Inputs Topography and Simulation Results for Final Design

Table D1: Node Input Table to Create NeatWork “Final Design” Topography File

T	0.00	0	0	0	0
N1	-24.38	0	0	0	1
N2	-28.40	0	0	0	1
N3	-48.97	0	0	0	1
N4	-50.52	0	0	0	1
N5	-52.10	0	0	0	1
N6	-51.92	0	0	0	1
N7	-51.77	0	0	0	1
N8	-52.73	0	0	0	1
N9	-56.87	0	0	0	1
N10	-60.50	0	0	0	1
N11	-71.50	0	0	0	1
N12	-70.61	0	0	0	1
N13	-70.51	0	0	0	1
N14	-70.05	0	0	0	1
N15	-69.72	0	0	0	1
N16	-61.49	0	0	0	1
N17	-58.17	0	0	0	1
N17.5	-52.00	0	0	0	1
N18	-51.64	0	0	0	1
N19	-50.47	0	0	0	1
N20	-70.61	0	0	0	1
N21	-56.29	0	0	0	1
N22	-56.29	0	0	0	1
N23	-70.54	0	0	0	1
N24	-71.09	0	0	0	1
N25	-71.09	0	0	0	1
N26	-52.27	0	0	0	1
N27	-61.26	0	0	0	1
N28	-64.00	0	0	0	1
N29.0	-60.00	0	0	0	1
N29.1	-72.09	0	0	0	1
N30	-44.58	0	0	0	1
N31	-46.75	0	0	0	1

Table D1: (Continued)

N32	-47.75	0	0	0	1
N33.0	-48.75	0	0	0	1
N33.1	-49.54	0	0	0	1
N34	-46.41	0	0	0	1
N35	-54.72	0	0	0	1
N36	-41.77	0	0	0	1
N37.0	-42.31	0	0	0	1
N37.5	-42.06	0	0	0	1
N38	-72.70	0	0	0	1
N39	-72.72	0	0	0	1
N40	-73.00	0	0	0	1
N41	-74.00	0	0	0	1
N42	-74.00	0	0	0	1
N43	-74.00	0	0	0	1
N44	-74.00	0	0	0	1
N45	-77.44	0	0	0	1
N46	-65.37	0	0	0	1
N47	-63.36	0	0	0	1
N48	-60.26	0	0	0	1
N49	-61.33	0	0	0	1
N50	-58.13	0	0	0	1
N51	-57.92	0	0	0	1
N52	-57.54	0	0	0	1
N53	-56.10	0	0	0	1
N54	-54.93	0	0	0	1
N55	-58.00	0	0	0	1
N56	-59.30	0	0	0	1
N57	-61.02	0	0	0	1
N58	-59.78	0	0	0	1
N59	-56.86	0	0	0	1
N60	-55.61	0	0	0	1
N61	-53.81	0	0	0	1
N62	-53.96	0	0	0	1
N63	-55.36	0	0	0	1
N64	-55.49	0	0	0	1
N65	-50.28	0	0	0	1
N66	-77.03	0	0	0	1
N67	-78.86	0	0	0	1
N68	-55.45	0	0	0	1
N69	-80.60	0	0	0	1

Table D1: (Continued)

N70	-78.20	0	0	0	1
N71	-75.64	0	0	0	1
N72	-75.85	0	0	0	1
N73	-74.48	0	0	0	1
N74	-74.25	0	0	0	1
N75	-74.04	0	0	0	1
N76	-64.49	0	0	0	1
N77	-71.55	0	0	0	1
N78	-59.39	0	0	0	1
N79	-57.61	0	0	0	1
N80	-52.53	0	0	0	1
N81	-49.84	0	0	0	1
N82	-51.03	0	0	0	1
N83	-51.26	0	0	0	1
N84	-55.25	0	0	0	1
N85	-56.29	0	0	0	1
N86	-68.00	0	0	0	1
N87	-66.30	0	0	0	1
N88	-69.93	0	0	0	1
N89	-73.12	0	0	0	1
N90	-64.28	0	0	0	1
N91	-60.37	0	0	0	1
N92	-59.69	0	0	0	1
N93	-51.74	0	0	0	1
N94	-51.81	0	0	0	1
P1	-52.17	0	0	1	2
P2	-54.17	0	0	1	2
P3	-53.72	0	0	1	2
P4	-57.30	0	0	1	2
P5	-56.82	0	0	1	2
P6	-60.50	0	0	1	2
P7	-70.74	0	0	1	2
P8	-70.49	0	0	1	2
P9	-68.30	0	0	1	2
P10	-58.95	0	0	1	2
P11	-59.87	0	0	1	2
P12	-45.24	0	0	1	2
P13	-50.42	0	0	1	2
P14	-47.57	0	0	1	2
P15	-55.47	0	0	1	2

Table D1: (Continued)

P16	-53.87	0	0	1	2
P17	-44.48	0	0	1	2
P18	-69.16	0	0	1	2
P19	-70.31	0	0	1	2
P20	-70.41	0	0	1	2
P21	-72.06	0	0	1	2
P22	-52.27	0	0	1	2
P23	-60.33	0	0	1	2
P24	-71.83	0	0	1	2
P25	-53.65	0	0	1	2
P26	-41.77	0	0	1	2
P27	-42.44	0	0	1	2
P28	-55.15	0	0	1	2
P29	-59.32	0	0	1	2
P30	-46.16	0	0	1	2
P31	-46.85	0	0	1	2
P32	-42.73	0	0	1	2
P33	-44.46	0	0	1	2
P34	-72.75	0	0	1	2
P35	-72.72	0	0	1	2
P36	-73.00	0	0	1	2
P37	-74.00	0	0	1	2
P38	-72.69	0	0	1	2
P39	-73.00	0	0	1	2
P40	-65.37	0	0	1	2
P41	-62.95	0	0	1	2
P42	-61.13	0	0	1	2
P43	-58.97	0	0	1	2
P44	-58.61	0	0	1	2
P45	-54.62	0	0	1	2
P46	-54.62	0	0	1	2
P47	-60.08	0	0	1	2
P48	-59.68	0	0	1	2
P49	-61.18	0	0	1	2
P50	-63.41	0	0	1	2
P51	-56.30	0	0	1	2
P52	-49.57	0	0	1	2
P53	-50.03	0	0	1	2
P54	-46.60	0	0	1	2
P55	-81.35	0	0	1	2

Table D1: (Continued)

P56	-78.41	0	0	1	2
P57	-75.66	0	0	1	2
P58	-74.48	0	0	1	2
P59	-74.17	0	0	1	2
P60	-73.64	0	0	1	2
P61	-64.87	0	0	1	2
P62	-41.46	0	0	1	2
P63	-58.22	0	0	1	2
P64	-49.08	0	0	1	2
P65	-49.79	0	0	1	2
P66	-50.90	0	0	1	2
P67	-55.68	0	0	1	2
P68	-55.20	0	0	1	2
P69	-39.86	0	0	1	2
P70	-60.76	0	0	1	2
P71	-66.61	0	0	1	2
P72	-68.54	0	0	1	2
P73	-64.82	0	0	1	2
P74	-53.26	0	0	1	2
P75	-51.86	0	0	1	2
P76	-51.94	0	0	1	2
P77	-69.60	0	0	1	2

Table D2: Arc Length Input Table to Create NeatWork "Final Design" Topography File

T	N1	206.47
N1	N2	32.05
N2	N3	93.54
N3	N4	12.20
N4	N5	24.40
N5	N6	11.60
N6	N7	6.70
N7	N8	22.10
N8	N9	30.50
N9	N10	25.77
N10	N11	120.50
N11	N12	66.60
N11	N12	66.60
N20	N13	25.00
N13	N14	15.00

Table D2: (Continued)

N14	N15	6.10
N15	N16	38.92
N16	N17	21.49
N17	N17.5	25.50
N17.5	N18	5.00
N18	N19	18.30
N12	N20	22.50
N20	N21	23.00
N21	N22	1.00
N12	N23	32.61
N23	N24	33.85
N24	N25	0.50
N8	N26	45.63
N26	N27	131.90
N27	N28	36.00
N28	N29.0	46.10
N7	N29.1	113.15
N29.1	N30	118.97
N30	N31	57.70
N31	N32	15.00
N32	N33.0	15.00
N33.0	N33.1	18.80
N33.1	N34	35.90
N34	N35	38.75
N30	N36	21.90
N36	N37.0	20.02
N32	N37.5	103.25
N29.0	N38	34.00
N38	N39	25.00
N38	N40	0.50
N40	N41	13.30
N41	N42	17.60
N42	N43	94.20
N43	N44	6.40
N44	N45	14.10
N45	N46	52.55
N46	N47	21.35
N47	N48	29.95
N48	N49	8.53
N48	N50	35.75

Table D2: (Continued)

N50	N51	7.10
N51	N52	47.80
N52	N53	24.40
N53	N54	42.70
N46	N47	21.35
N47	N48	29.95
N48	N49	8.53
N48	N50	35.75
N50	N51	7.10
N51	N52	47.80
N52	N53	24.40
N53	N54	42.70
N54	N55	46.79
N55	N56	24.40
N56	N57	36.60
N57	N58	36.60
N58	N59	26.22
N59	N60	24.40
N60	N61	24.40
N61	N62	6.10
N62	N63	6.10
N63	N64	2.70
N63	N65	72.02
N42	N66	26.00
N66	N67	4.20
N67	N68	47.53
N68	N69	67.10
N69	N70	21.74
N69	N71	139.00
N71	N72	21.35
N72	N73	18.30
N73	N74	18.30
N74	N75	6.10
N75	N76	79.85
N72	N77	61.80
N77	N78	42.64
N78	N79	12.00
N79	N80	30.00
N80	N81	23.50
N81	N82	20.60

Table D2: (Continued)

N82	N83	3.90
N83	N84	29.69
N77	N85	230.00
N85	N86	68.99
N86	N87	7.00
N87	N88	35.68
N88	N89	20.00
N89	N90	47.97
N90	N91	37.87
N91	N92	6.00
N92	N93	47.48
N93	N94	18.00
N3	P1	19.37
N4	P2	13.07
N5	P3	9.63
N6	P4	145.67
N9	P5	18.30
N10	P6	0.50
N11	P7	25.00
N13	P8	11.80
N14	P9	19.83
N16	P10	17.25
N17	P11	34.30
N18	P12	40.18
N19	P13	12.20
N19	P14	36.60
N21	P15	2.70
N22	P16	26.88
N17.5	P17	80.00
N23	P18	18.30
N24	P19	18.30
N25	P20	14.87
N25	P21	54.90
N26	P22	20.00
N27	P23	20.00
N28	P24	35.00
N33.1	P25	9.80
N36	P26	6.00
N37.0	P27	12.00
N34	P28	6.00

Table D2: (Continued)

N35	P29	33.03
N33.0	P30	20.00
N32	P31	20.00
N37.5	P32	6.00
N37.5	P33	35.50
N39	P34	10.00
N39	P35	10.00
N40	P36	20.00
N41	P37	20.00
N43	P38	18.77
N44	P39	0.50
N46	P40	0.50
N49	P41	64.58
N49	P42	4.50
N50	P43	13.00
N52	P44	26.27
N53	P45	35.90
N54	P46	20.20
N55	P47	28.70
N56	P48	6.10
N58	P49	50.84
N60	P50	72.92
N64	P51	4.80
N64	P52	17.31
N65	P53	6.10
N65	P54	23.00
N68	P55	13.55
N70	P56	5.00
N70	P57	40.04
N73	P58	0.50
N74	P59	12.20
N75	P60	12.20
N76	P61	8.00
N77	P62	66.74
N78	P63	6.00
N79	P64	10.43
N80	P65	6.00
N81	P66	1.20
N82	P67	14.60
N83	P68	3.00

Table D2: (Continued)

N84	P69	153.75
N85	P70	45.88
N88	P71	64.95
N89	P72	66.76
N90	P73	6.00
N92	P74	36.48
N93	P75	30.00
N94	P76	6.00
N91	P77	150.00

Table D3: NeatWork Simulation Results for “Final Design” Design File

Faucet Idea	**No. of Occurrences**	**Min Flow (L/s)**	**Average Flow (L/s)**	**Max Flow (L/s)**	**Variability (%)**	**Flow <0.1 L/s (%)**	**Flow <0.3 L/s (%)**	**No. of Failures**
Global average			0.1899			1.23	0.71	0
P1	35	0.1937	0.1943	0.1954	0.21	0	0	0
P10	46	0.1647	0.2023	0.2803	12.63	0	0	0
P11	31	0.1644	0.1992	0.2705	11.01	0	0	0
P12	49	0.0792	0.1969	0.3451	28.31	4.08	4.08	0
P13	37	0.1397	0.2062	0.3113	19.05	0	2.7	0
P14	39	0.1327	0.2263	0.373	23.26	0	12.82	0
P15	37	0.1616	0.1865	0.2316	9.73	0	0	0
P16	35	0.1489	0.1841	0.2495	11.02	0	0	0
P17	36	0.0232	0.1851	0.3571	38.61	11.11	8.33	0
P18	38	0.1245	0.155	0.1846	10.07	0	0	0
P19	39	0.1545	0.2152	0.2624	12.76	0	0	0
P2	40	0.1959	0.1967	0.1983	0.24	0	0	0
P20	36	0.1554	0.22	0.2925	15.1	0	0	0
P21	45	0.1576	0.2184	0.2964	13.56	0	0	0
P22	36	0.1741	0.1769	0.1798	0.74	0	0	0
P23	41	0.1788	0.1837	0.1898	1.26	0	0	0
P24	39	0.1978	0.2027	0.2094	1.17	0	0	0
P25	43	0.1321	0.1811	0.2526	15.77	0	0	0
P26	39	0.1605	0.1895	0.236	9.83	0	0	0
P27	41	0.1596	0.1887	0.2182	8.71	0	0	0
P28	39	0.1233	0.1772	0.2424	17.92	0	0	0

Table D3: (Continued)

P29	38	0.1405	0.178	0.2291	12.78	0	0	0
P3	41	0.1904	0.1915	0.1933	0.29	0	0	0
P30	39	0.129	0.2034	0.314	20.22	0	2.56	0
P31	46	0.1635	0.2266	0.323	17.43	0	6.52	0
P32	38	0.0582	0.1912	0.3404	37.13	10.53	2.63	0
P33	37	0.1123	0.1918	0.3098	27.35	0	5.41	0
P34	45	0.1882	0.1958	0.2066	2.05	0	0	0
P35	44	0.1882	0.1958	0.2046	2.07	0	0	0
P36	35	0.1946	0.2009	0.2101	1.56	0	0	0
P37	33	0.1956	0.2021	0.2096	1.53	0	0	0
P38	41	0.1844	0.1945	0.2028	1.96	0	0	0
P39	39	0.1863	0.1965	0.2068	2.14	0	0	0
P4	41	0.1837	0.1849	0.1863	0.33	0	0	0
P40	39	0.165	0.1768	0.1952	3.2	0	0	0
P41	50	0.1493	0.1648	0.1837	3.7	0	0	0
P42	41	0.149	0.1635	0.1743	3.44	0	0	0
P43	43	0.1435	0.1577	0.1716	3.37	0	0	0
P44	34	0.1994	0.2202	0.2509	4.65	0	0	0
P45	40	0.1703	0.1973	0.2223	5.51	0	0	0
P46	42	0.1584	0.1956	0.2354	8.79	0	0	0
P47	47	0.1743	0.209	0.2472	7.66	0	0	0
P48	44	0.1728	0.2059	0.2442	7.67	0	0	0
P49	41	0.1661	0.2004	0.2436	9.3	0	0	0
P5	38	0.1877	0.1893	0.192	0.48	0	0	0
P50	48	0.1707	0.2003	0.2475	7.91	0	0	0
P51	40	0.1451	0.1774	0.2399	11.32	0	0	0
P52	33	0.1178	0.1826	0.2516	17.54	0	0	0
P53	31	0.1392	0.185	0.2575	19.19	0	0	0
P54	40	0.0465	0.1843	0.3197	41.94	22.5	5	0
P55	45	0.204	0.2113	0.2202	1.71	0	0	0
P56	39	0.1877	0.198	0.209	2.57	0	0	0
P57	42	0.1787	0.1891	0.2015	2.85	0	0	0
P58	41	0.1668	0.18	0.1978	4.08	0	0	0
P59	37	0.1564	0.1739	0.1911	5.96	0	0	0
P6	48	0.1892	0.1922	0.1987	1.11	0	0	0
P60	35	0.1532	0.17	0.188	5.74	0	0	0
P61	40	0.1791	0.2073	0.234	7.29	0	0	0
P62	45	0.1164	0.1852	0.2544	16.87	0	0	0

Table D3: (Continued)

P63	38	0.192	0.2139	0.2429	6.19	0	0	0
P64	37	0.1394	0.1706	0.2031	8.71	0	0	0
P65	36	0.1423	0.1675	0.2095	8.85	0	0	0
P66	46	0.1528	0.1795	0.215	8.57	0	0	0
P67	37	0.1734	0.1982	0.2273	6.66	0	0	0
P68	44	0.1758	0.195	0.2324	6.02	0	0	0
P69	53	0.0518	0.1341	0.2085	27.72	22.64	0	0
P7	38	0.1755	0.185	0.2002	3.54	0	0	0
P70	47	0.1706	0.1969	0.2346	7.27	0	0	0
P71	32	0.1682	0.2041	0.2559	10.26	0	0	0
P72	40	0.1738	0.2104	0.2494	8.5	0	0	0
P73	39	0.1608	0.2018	0.2621	11.67	0	0	0
P74	51	0.0804	0.1716	0.2629	21.69	3.92	0	0
P75	41	0.0563	0.1872	0.2849	25.21	7.32	0	0
P76	39	0.0647	0.2022	0.3113	26.13	5.13	5.13	0
P77	39	0.1132	0.1347	0.1636	8.38	0	0	0
P8	44	0.1512	0.1695	0.2108	7.19	0	0	0
P9	38	0.1431	0.1623	0.189	7.72	0	0	0

Appendix E: Calculations of Available Head at Each Faucet

Equations used in calculating available head are:

$$Re = \frac{d * v}{\mathrm{v}} \tag{E1}$$

where:

v = *1.0 x 10^{-6} m^{s}/s (Crowe et al., 2010)*

$$f = \frac{0.25}{\left[log_{10}\left(\frac{k_S}{3.7D}+\frac{5.74}{Re^{0.9}}\right)\right]^2} \tag{2}$$

$$h_L = f \frac{\mathrm{L}}{\mathrm{D}} \frac{\mathrm{v}^2}{2g} \tag{1}$$

$$Total\ Headloss = \sum h_L \tag{E2}$$

$$Available\ Head = -E - h_L \tag{E3}$$

Table E1: Spreadsheet Used to Calculate Available Head at Each Faucet

Start	**End**	**Length, L (m)**	**Pipe Diameter, d (m)**	**Average Veloc-ity, v (m/s)**	**Reynolds Number, Re**	**Friction Factor, *f***	**Head-loss, h_L (m)**	**Total Head-loss (m)**	**Relative Elevation, E (m)**	**Calculated Available Head (m)**
T	N1	14.85	0.082	1.06	86920	0.018	0.19	0.19	-4.0	3.8
N1	N2	17.2	0.082	1.06	86920	0.018	0.22	0.41	-2.6	2.2

Table E1: (Continued)

N2	N3	93.54	0.082	1.06	86920	0.018	1.20	1.61	-24.6	23.0
N3	N4	12.2	0.082	1.04	85280	0.018	0.15	1.77	-26.1	24.4
N4	N5	24.4	0.082	1.03	84460	0.019	0.30	2.06	-27.7	25.6
N5	N6	11.6	0.082	1.01	82820	0.019	0.14	2.20	-27.5	25.3
N6	N7	6.7	0.082	0.99	81180	0.019	0.08	2.28	-27.4	25.1
N7	N8	22.1	0.082	0.99	81180	0.019	0.25	2.53	-28.3	25.8
N8	N9	42.7	0.0446	0.85	37910	0.022	0.78	3.31	-32.5	29.2
N9	N10	25.77	0.0446	0.79	35234	0.023	0.41	3.72	-36.1	32.4
N10	N10$	54	0.0446	0.72	32112	0.023	0.74	4.46		
N10$	N11	46.76	0.0304	1.56	47424	0.021	4.01	8.47	-47.1	38.6
N11	N12	48.8	0.0304	1.45	44080	0.021	3.68	12.15	-46.2	34.1
N12	N13	12.2	0.0304	0.74	22496	0.025	0.28	12.43	-46.1	33.7
N13	N14	15	0.0304	0.63	19152	0.026	0.26	12.69	-45.7	33.0
N14	N15	6.1	0.0304	0.49	14896	0.028	0.07	12.76	-45.3	32.6
N15	N16	38.92	0.0304	0.49	14896	0.028	0.44	13.19	-37.1	23.9
N16	N17	21.49	0.0304	0.4	12160	0.029	0.17	13.36	-33.8	20.4
N17	N18	30.5	0.0304	0.3	9120	0.032	0.15	13.51	-27.3	13.7
N18	N19	18.3	0.0182	0.57	10374	0.031	0.51	14.02	-26.1	12.1
N12	N20	37.433	0.0304	0.33	10032	0.031	0.21	12.36	-45.7	33.4
N20	N21	29.958	0.0304	0.33	10032	0.031	0.17	12.53	-36.7	24.2
N21	N22	23.322	0.0304	0.33	10032	0.031	0.13	12.66	-31.9	19.2
N12	N23	32.61	0.0182	1.07	19474	0.026	2.72	14.86	-46.2	31.3
N23	N24	33.85	0.0182	0.8	14560	0.028	1.70	16.56	-46.7	30.1
N8	N25	12.2	0.082	0.74	60680	0.020	0.08	2.61	-27.9	25.3
N25	N26	33.43	0.082	0.74	60680	0.020	0.23	2.84	-27.9	25.1
N26	N27	48.8	0.082	0.72	59040	0.020	0.31	3.15	-33.6	30.4
N27	N28	5	0.082	0.72	59040	0.020	0.03	3.18	-36.9	33.7
N28	N29	42.85	0.0557	1.53	85221	0.018	1.70	4.88	-38.4	33.5

Table E1: (Continued)

N29	N30	4.5	0.0557	1.53	85221	0.018	0.18	5.06	-38.9	33.8
N30	N31	7.8	0.0304	1.04	31616	0.023	0.33	5.39	-37.1	31.7
N31	N32	34.08	0.0304	1.04	31616	0.023	1.43	6.81	-49.5	42.7
N32	N33	59.35	0.0304	1.04	31616	0.023	2.49	9.30	-29.3	20.0
N33	N34	6.1	0.0304	1.04	31616	0.023	0.26	9.55	-29.1	19.5
N34	N35	20.7	0.0304	0.94	28576	0.024	0.73	10.28	-25.8	15.5
N35	N36	35.9	0.0304	0.62	18848	0.026	0.61	10.89	-22.6	11.7
N36	N37*	36.25	0.0182	0.54	9828	0.031	0.92	11.81	-30.9	19.1
N36	N38	1.55	0.0304	0.43	13072	0.029	0.01	10.90	-22.7	11.8
N38	N39	10.07	0.0304	0.3	9120	0.032	0.05	10.95	-23.9	12.9
N39	N39$	73.24	0.0304	0.2	6080	0.036	0.18	11.12		
N39$	N40	30	0.0182	0.56	10192	0.031	0.81	11.93	-17.7	5.7
N35	N41	48.8	0.0304	0.31	9424	0.031	0.25	10.53	-23.0	12.4
N41	N41$	17.2	0.0304	0.21	6384	0.035	0.04	10.57		
N41$	N42	15.5	0.0182	0.57	10374	0.031	0.43	11.00	-20.8	9.8
N30	N43	2.3	0.0557	1.22	67954	0.019	0.06	5.12	-39.2	34.1
N43	N44	18.3	0.0557	1.22	67954	0.019	0.48	5.60	-40.4	34.8
N44	N45	16.08	0.0557	1.22	67954	0.019	0.42	6.03	-55.4	49.3
N45	N46	37.2	0.0557	1.22	67954	0.019	0.98	7.01	-48.3	41.3
N46	N47	30.5	0.0446	0.91	40586	0.022	0.63	7.64	-47.6	40.0
N47	N48	40	0.0446	0.91	40586	0.022	0.82	8.46	-48.3	39.9
N48	N49	50	0.0446	0.82	36572	0.022	0.86	9.32	-52.7	43.3
N49	N50	4.2	0.0446	0.82	36572	0.022	0.07	9.39	-54.5	45.1
N50	N51	139	0.0446	0.82	36572	0.022	2.38	11.78	-51.3	39.5
N51	N52	21.35	0.0446	0.82	36572	0.022	0.37	12.14	-51.5	39.3
N52	N53	18.3	0.0182	1.15	20930	0.026	1.73	13.87	-50.1	36.2
N53	N54	18.3	0.0182	0.85	15470	0.028	1.02	14.89	-49.9	35.0
N54	N55	6.1	0.0182	0.55	10010	0.031	0.16	15.05	-49.7	34.6

Table E1: (Continued)

N55	N56	79.85	0.0182	0.3	5460	0.037	0.74	15.80	-40.1	24.3
N46	N57	12.2	0.0446	0.98	43708	0.021	0.29	7.30	-48.9	41.6
N57	N58	18.7	0.0446	0.89	39694	0.022	0.37	7.67	-48.6	40.9
N58	N59	49.1	0.0446	0.84	37464	0.022	0.88	8.55	-53.1	44.5
N59	N60	52.55	0.0446	0.84	37464	0.022	0.94	9.49	-41.0	31.5
N60	N61	21.35	0.0446	0.77	34342	0.023	0.33	9.81	-39.0	29.2
N61	N62	29.95	0.0446	0.77	34342	0.023	0.46	10.27	-35.9	25.6
N62	N63	8.53	0.0182	0.29	5278	0.037	0.07	10.35	-36.9	26.6
N62	N64	35.75	0.0446	0.68	30328	0.023	0.44	10.71	-33.7	23.0
N64	N65	7.1	0.0446	0.63	28098	0.024	0.08	10.79	-33.5	22.7
N65	N66	47.8	0.0446	0.63	28098	0.024	0.51	11.31	-33.2	21.9
N66	N67	24.4	0.0446	0.58	25868	0.024	0.23	11.53	-31.7	20.2
N67	N67$	28.79	0.0446	0.53	23638	0.025	0.23	11.76		
N67$	N68	13.91	0.0304	1.13	34352	0.023	0.67	12.44	-30.5	18.1
N68	N69	46.79	0.0304	1.03	31312	0.023	1.93	14.36	-33.6	19.3
N69	N70	24.4	0.0304	0.92	27968	0.024	0.82	15.19	-34.9	19.7
N70	N71	36.6	0.0304	0.81	24624	0.025	0.99	16.17	-36.6	20.5
N71	N72	36.6	0.0304	0.81	24624	0.025	0.99	17.16	-35.4	18.2
N72	N73	26.22	0.0304	0.57	17328	0.027	0.38	17.54	-32.5	14.9
N73	N74	24.4	0.0304	0.48	14592	0.028	0.26	17.81	-31.2	13.4
N74	N75	24.4	0.0304	0.39	11856	0.030	0.18	17.99	-29.4	11.4
N75	N76	6.1	0.0304	0.39	11856	0.030	0.05	18.04	-29.6	11.5
N76	N77	6.1	0.0304	0.39	11856	0.030	0.05	18.08	-31.0	12.9
N77	N78	2.7	0.0182	0.57	10374	0.031	0.08	18.16	-31.1	12.9
N77	N79	72.02	0.0304	0.18	5472	0.037	0.14	18.23	-25.9	7.7
N52	N80	61.8	0.0446	0.62	27652	0.024	0.65	12.79	-47.2	34.4
N80	N81	42.64	0.0446	0.62	27652	0.024	0.45	18.67	-35.0	16.3
N81	N82	12	0.0446	0.59	26314	0.024	0.12	12.91	-33.2	20.3

Table E1: (Continued)

N82	N83	30	0.0446	0.53	23638	0.025	0.24	18.91	-28.1	9.2
N83	N84	23.5	0.0446	0.48	21408	0.025	0.16	13.06	-25.5	12.4
N84	N85	20.6	0.0446	0.44	19624	0.026	0.12	19.03	-26.6	7.6
N85	N86	3.9	0.0446	0.38	16948	0.027	0.02	13.08	-26.9	13.8
N86	N87	29.69	0.0446	0.34	15164	0.028	0.11	19.14	-30.9	11.7
N87	N88	6	0.0446	0.29	12934	0.029	0.02	13.10	-31.9	18.8
N88	N89	68.99	0.0304	0.58	17632	0.027	1.04	20.18	-43.6	23.4
N89	N90	7	0.0304	0.47	14288	0.028	0.07	13.17	-41.9	28.7
N90	N90$	22.68	0.0304	0.47	14288	0.028	0.24	20.41		
N90$	N91	13	0.0304	1.3	39520	0.022	0.81	13.98	-45.5	31.6
N91	N92	20	0.0182	1.02	18564	0.026	1.53	21.95	-48.7	26.8
N92	N93	47.97	0.0182	0.67	12194	0.029	1.77	15.75	-39.9	24.2
N93	N94	37.87	0.0182	0.42	7644	0.033	0.62	22.57	-36.0	13.4
N94	N95	6	0.0182	0.42	7644	0.033	0.10	15.85	-35.3	19.5
N95	N96	47.48	0.0182	0.26	4732	0.038	0.35	22.92	-27.4	4.4
N96	N97	18	0.0182	0.26	4732	0.038	0.13	15.98	-27.4	11.5
N11	N1*	2.14	0.0182	0.3	5460	0.037	0.02	8.49	-45.8	37.3
N18	N2*	6.1	0.0182	0.27	4914	0.038	0.05	13.56	-25.9	12.3
N2*	N3*	27.98	0.0182	0.27	4914	0.038	0.22	8.71	-20.3	11.6
N39	N4*	22.45	0.0182	0.29	5278	0.037	0.20	11.14	-22.5	11.4
N88	N6*	65.5	0.0304	0.05	1520	0.056	0.02	8.72	-41.7	33.0
N91	N7*	10.95	0.0182	0.28	5096	0.038	0.09	14.07	-40.1	26.0
N7*	N8*	24	0.0182	0.28	5096	0.038	0.20	22.15	-38.2	16.1
N92	N9*	8	0.0182	0.36	6552	0.035	0.10	15.85	-45.0	29.2
N57	N5*	6.1	0.0182	0.69	12558	0.029	0.24	7.54	-48.3	40.8
N3	P1	19.37	0.0182	0.83	15106	0.028	1.04	2.65	-27.8	25.1
N4	PN1	13.07	0.0182	0.86	15652	0.027	0.74	2.51	-29.8	27.3
N5	P2	9.63	0.0182	0.85	15470	0.028	0.54	2.60	-29.3	26.7

Table E1: (Continued)

N6	P3	145.67	0.0182	0.8	14560	0.028	7.31	9.51	-32.9	23.4
N9	P4	18.3	0.0182	0.87	15834	0.027	1.06	4.37	-32.4	28.1
N10	P5	0.5	0.0182	0.93	16926	0.027	0.03	3.75	-36.1	32.4
N1*	P6	8.64	0.0182	0.66	12012	0.029	0.31	8.80	-46.4	37.6
N13	P7	11.8	0.0182	0.91	16562	0.027	0.74	13.17	-46.1	32.9
N14	P8	19.83	0.0182	0.87	15834	0.027	1.15	13.84	-43.9	30.1
N16	P9	17.25	0.0182	0.72	13104	0.029	0.72	13.91	-34.6	20.7
N17	P10	34.3	0.0182	0.71	12922	0.029	1.40	14.76	-35.5	20.7
N19	P11	12.2	0.0182	0.76	13832	0.028	0.56	14.58	-26.0	11.5
N19	P12	36.6	0.0182	0.71	12922	0.029	1.49	15.51	-23.2	7.7
N3*	P13	6.1	0.0182	0.77	14014	0.028	0.29	8.99	-20.9	11.9
N22	P14	55	0.0182	0.68	12376	0.029	2.08	14.74	-20.1	5.4
N22	P15	2.7	0.0182	0.9	16380	0.027	0.17	12.83	-31.1	18.3
N22	P16	26.88	0.0182	0.82	14924	0.028	1.41	14.07	-29.5	15.4
N23	P17	18.3	0.0182	0.82	14924	0.028	0.96	15.82	-44.8	29.0
N24	P18	18.3	0.0182	0.77	14014	0.028	0.86	17.42	-45.9	28.5
N24	P19	14.87	0.0182	0.79	14378	0.028	0.73	17.29	-46.0	28.7
N24	PN2	54.9	0.0182	0.76	13832	0.028	2.52	19.09	-47.7	28.6
N26	P20	0.8	0.0182	0.82	14924	0.028	0.04	2.88	-27.9	25.0
N28	PN3	14.1	0.0182	0.93	16926	0.027	0.92	4.10	-35.9	31.8
N37*	P21	2.5	0.0182	0.67	12194	0.029	0.09	11.90	-31.4	19.5
N37*	P22	35.53	0.0182	0.72	13104	0.029	1.49	13.29	-35.5	22.2
N34	P23	30.5	0.0182	0.69	12558	0.029	1.18	10.74	-29.9	19.1
N38	P24	4.78	0.0182	0.87	15834	0.027	0.28	11.18	-22.4	11.2
N4*	P25	31.75	0.0182	0.77	14014	0.028	1.49	12.64	-23.1	10.4
N40	P26	0.5	0.0182	0.67	12194	0.029	0.02	11.95	-17.3	5.4
N40	P27	35.5	0.0182	0.71	12922	0.029	1.45	13.38	-19.1	5.7
N41	PN4	8.54	0.0182	0.75	13650	0.028	0.38	10.91	-23.8	12.9

Table E1: (Continued)

N42	P28	42.7	0.0182	0.75	13650	0.028	1.92	12.92	-18.0	5.1
N42	P29	20.85	0.0182	0.81	14742	0.028	1.07	12.07	-19.8	7.7
N57	P30	24.87	0.0182	0.69	12558	0.029	0.97	8.26	-48.3	40.0
N58	P31	0.5	0.0182	0.69	12558	0.029	0.02	7.69	-48.6	40.9
N60	P32	0.5	0.0182	0.91	16562	0.027	0.03	9.52	-41.0	31.5
N62	P33	64.58	0.0182	0.8	14560	0.028	3.24	13.52	-38.6	25.1
N63	P34	4.5	0.0182	0.82	14924	0.028	0.24	10.59	-36.7	26.2
N64	P35	13	0.0182	0.78	14196	0.028	0.62	11.34	-34.6	23.2
N66	P36	26.27	0.0182	0.75	13650	0.028	1.18	12.49	-34.2	21.7
N67	P37	35.9	0.0182	0.66	12012	0.029	1.29	12.82	-30.2	17.4
N68	PN5	20.2	0.0182	0.65	11830	0.030	0.71	13.14	-30.2	17.1
N69	P38	28.7	0.0182	0.71	12922	0.029	1.17	15.53	-35.7	20.2
N70	P39	6.1	0.0182	0.7	12740	0.029	0.24	15.43	-35.3	19.9
N72	P40	50.84	0.0182	0.66	12012	0.029	1.83	18.99	-36.8	17.8
N73	P41	11	0.0182	0.79	14378	0.028	0.54	18.08	-33.7	15.6
N74	P42	72.92	0.0182	0.67	12194	0.029	2.69	20.50	-39.0	18.5
N78	P43	4.8	0.0182	0.74	13468	0.029	0.21	18.37	-31.9	13.5
N78	P44	17.31	0.0182	0.64	11648	0.030	0.59	18.75	-25.2	6.4
N79	N79$	17	0.0304	0.17	5168	0.037	0.03	18.26		
N79$	P45	6	0.0182	0.23	4186	0.040	0.04	18.29	-22.2	3.9
N79	PN6	6.1	0.0182	0.7	12740	0.029	0.24	18.47	-25.6	7.2
N72	P46	14.2	0.0182	0.86	15652	0.027	0.81	17.97	-47.4	29.5
N48	P47	6.9	0.0182	0.68	12376	0.029	0.26	8.73	-48.3	39.6
N48	P48	7.53	0.0182	0.68	12376	0.029	0.29	8.75	-48.4	39.6
N53	PN7	0.5	0.0182	0.64	11648	0.030	0.02	13.89	-50.1	36.2
N54	PN8	12.2	0.0182	0.61	11102	0.030	0.38	15.28	-49.8	34.5
N55	P49	12.2	0.0182	0.6	10920	0.030	0.37	15.43	-49.3	33.8
N56	P50	8	0.0182	0.7	12740	0.029	0.32	16.12	-40.5	24.4

Table E1: (Continued)

N81	P51	66.74	0.0182	0.5	9100	0.032	1.49	20.16	-17.1	-3.1
N82	PN9	6	0.0182	0.64	11648	0.030	0.20	13.11	-33.8	20.7
N83	PN10	10.43	0.0182	0.69	12558	0.029	0.41	19.32	-24.7	5.4
N84	P52	6	0.0182	0.71	12922	0.029	0.24	13.31	-25.4	12.1
N85	P53	1.2	0.0182	0.76	13832	0.028	0.06	19.09	-26.5	7.4
N86	P54	14.6	0.0182	0.65	11830	0.030	0.51	13.59	-31.3	17.7
N87	P55	3	0.0182	0.65	11830	0.030	0.11	19.25	-30.8	11.6
N6*	N6*$	147.75	0.0304	0.1	3040	0.044	0.11	8.83		
N6*$	P56	6	0.0182	0.13	2366	0.048	0.01	8.85	-15.5	6.6
N89	P57	45.88	0.0182	0.69	12558	0.029	1.78	21.96	-36.4	14.4
N8*	P58	30	0.0182	0.73	13286	0.029	1.28	23.43	-42.2	18.8
N9*	P59	58.76	0.0182	0.73	13286	0.029	2.52	18.37	-44.2	25.8
N93	PN11	6	0.0182	0.66	12012	0.029	0.22	15.96	-40.4	24.5
N95	PN12	36.48	0.0182	0.43	7826	0.033	0.63	16.47	-28.9	12.4
N97	P60	6	0.0182	0.37	6734	0.035	0.08	16.06	-27.5	11.4
N97	PN13	30	0.0182	0.38	6916	0.034	0.42	16.39	-27.6	11.2

Appendix F: Determining an Appropriate Number of Future Connections

The current standard for assuring water sources will have enough water in the future is to calculate the water needs of a future population calculated by a growth rate equation over the life of the aqueduct, typically 20 years. Assuming the average number of people per house remains constant as houses are added to the system, the same growth rate equation, Equation 9, can be used to calculate the future number of connections needed as follows:

$$C_N = C_O * \left(1 + \frac{r \times N}{100}\right) \quad \text{(F1)}$$

In Equation F1:

C_N = *the future number of connections*

C_0 = *the current number of connections*

R = *rate of growth*

N = *number of years*

The confirmed Santa Cruz aqueduct has 60 connections. Using Equation F1 and the Panamanian growth rate of 1.32% (CIA World Factbook, 2016), the projected number of connections for the Santa Cruz aqueduct in 20 years is calculated to be 75 connections or 15 new connections.

The author ran an analysis on an aqueduct that would have 13 new connections which is 2 less than the projected number of connections based on the modeled population growth. While adding two additional houses will continue to decrease the quality of service, it will not be significant enough to hurt the sustainability of the aqueduct. Therefore, using 13 houses for the analysis is appropriate for this analysis and represents a reasonable number of houses that could be added to the aqueduct in the future.

The author demonstrated that the Santa Cruz aqueduct still works at a reliable level of service when additional connections are added in conjunction with the predicted number of future connections based on the population growth rate. The author assumes that this will hold true for other aqueducts during their life as connections are added, but there is no evidence to support this claim. As stated earlier, for best results the designer should include all known potential connections in the design to minimize reductions in service quality throughout the life of the aqueduct.

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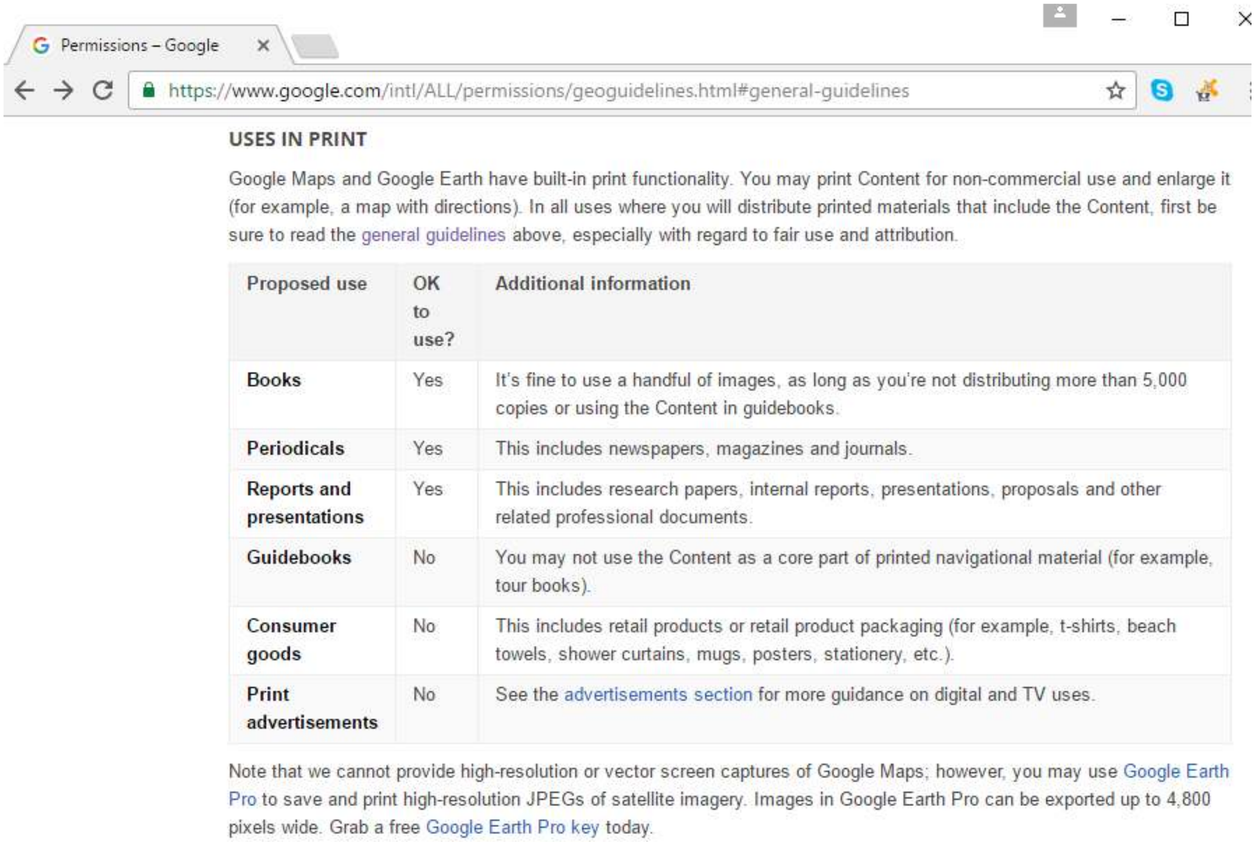

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