Validating the Accuracy of Neatwork, a Rural Gravity Fed Water Distribution System Design Program, Using Field Data in the Comarca Ngöbe-Bugle, Panama

by

Maria Briones

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Civil Engineering
Department of Civil and Environmental Engineering
College of Engineering
University of South Florida

Major Professor: James R. Mihelcic, Ph.D.
Mauricio Arias, Ph.D.
Mark Rains, Ph.D.

Date of Approval:
May 4, 2018

Keywords: Flow reducer, Sustainable Development Goals**,** Equity

ACKNOWLEDGEMENTS

I would like to first and foremost thank my family for the support they have given me since childhood. Without the steady support, good example and constant encouragement, none of this would be possible.

I would also like to thank Dr. Mihelcic for his mentoring, near and far, that gave me valuable and constructive insight into the world of academic research and investigation while simultaneously giving me the freedom to explore the world of development and immerse myself in the community in which I worked and lived. Many thanks to Dr. Arias for also guiding me through statistical methods and making me feel welcome in his office (or inbox).

Lastly, I would like to thank my Peace Corps host community of Alto Nube and Guary in the Comarca Ngabe-Bugle. Without the constant optimism, hard work, and kindness they exhibit every day, this work would not have been possible. A special thank you to my host family for being a home away from home and sharing your time, food, and stories with me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Despite the sustainable development goals to increase access to improved water there are still 884 million people in the world without access to an improved water source (WHO, 2017). One method to improve access to water in rural, mountainous areas, is through construction of gravity fed water distribution systems. These systems should be designed based upon fundamental principles of hydraulics. One method of doing so in a time efficient manner with minimal engineering knowledge is to utilize a downloadable computer program such as Neatwork, which aids in design of rural, gravity fed water distribution systems and has been used by volunteers in Peace Corps Panama for years. It was the goal of this research to validate the results of the Neatwork program by comparing the flow results produced in the simulation program with flow results measured at tap stands of a rural gravity fed water distribution system in the community of Alto Nube, Comarca Ngöbe Bugle, Panama.

The author measured flow under default Neatwork conditions of 40% faucets open in the system (in the field an equivalent of 8 taps) to have an initial basis as to whether the Neatwork program and field conditions yielded corresponding flows. The second objective would be to vary the number of taps open if the default condition did not produce comparable results between the field and the simulation, to pinpoint if under a certain condition of open faucets in the system the two methods would agree. The author did this by measuring flow at varying combinations from 10-100% of the open taps in the system (2-20 taps). Lastly the author observed the flow differences in the Neatwork program against the field flows, when the elevation of water in the water reservoir is set to the Neatwork default, where elevation of water is the tank outlet (at the bottom of the tank)

versus when the elevation is established at the overflow at the tank (at the top of the tank) for the case of two taps open.

The author used paired t-tests to test for statistical difference between Neatwork and field produced flows. She found that for the default condition of 40% taps open and all other combinations executed between 30-80% taps open, the field and Neatwork flows did not produce statistically similar results and, in fact, had the tendency to overestimate flows. The author also found that the change in water elevation in the storage tank from outlet to overflow increased the flow at the two taps measured by 0.140 l/s and 0.145 l/s and in this case, did not change whether the flows at these taps were within desired range (0.1 -0.3 l/s). Changing the elevation of the water level in the tank in the Neatwork program to correspond to a “full” tank condition is not recommended, as assuming an empty tank will account for seasonal changes or other imperfections in topographical surveying that could reduce available head at each tap. The author also found that the orifice coefficients, θ, of 0.62 and 0.68, did not demonstrate more or less accurate results that coincided with field measurements, but rather showed the tendency of particular faucets to prefer one coefficient over the other, regardless of combination of other taps open in the system.

This study demonstrates a consistent overestimation in flow using the computer program Neatwork. Further analysis on comparisons made show that between field and flow results across each individual faucet, variations between Neatwork and the field were a result of variables dependent upon the tap, such as flow reducers or errors in surveying. Flow reducers are installed before taps to distribute flow equally amongst homes over varying distances and elevations and are fabricated using different diameter orifices depending on the location of the tap. While Neatwork allows the user to simulate the effect of these flow reducers on tap flow, it may not account for the imperfect orifices made by the simple methods used in the field to make such flow reducers.

The author recommends further investigation to be done on the results of field flow versus Neatwork simulated flow using other methods of flow reducer fabrication which produce varying degrees of accuracy in orifice sizing. The author also recommends executing these field measurements over a greater sample size of faucets and more randomized combination of open/closed taps to verify the results of this research. More work should be done to come up with a practical solution for poor and rural communities to fabricate and/or obtain more precisely sized flow reducers. A full sensitivity analysis of the input variables into the Neatwork program should be performed to understand the sensitivity of varying each input.

CHAPTER 1. INTRODUCTION TO RURAL GRAVITY FED WATER DISTRIBUTION SYSTEMS

1.1 Access to Water Globally

In 1990 the United Nations established the Millennium Development Goals (MDGs) in order to improve the state of the developing world. The MDGs had a total of 17 goals, ranging from decreasing poverty, to increasing food security and access to water and sanitation (United Nations 1990). Since the culmination of the MDGs in 2015, the Sustainable Development Goals (SDGs) were put into place on January 1st, 2016 to continue to work on the most essential needs of the world's citizens. SDG Number 6, targets the availability and sustainability of safe water and sanitation for all, with Target 6.1 specifically stating: "By 2030 achieve universal and equitable access to safe and affordable drinking water for all" (UNICEF/WHO 2017).

Yet even with global action created based on the MDGs and SDGs, as of July 2017, there are 884 million people in the world still without access to an improved water source (WHO, 2017). This means that there is still substantial work to be done in the field to achieve equal access to safe water to people of the world. Furthermore, the transition from the MDGs to SDGs recognizes that there is a need to push further for the global communities and national and local governments to serve the most marginalized groups of the world that have not been able to have access to such a basic commodity.

1.2 Peace Corps in Panama

Peace Corps, a U.S. governmental volunteer agency, has worked in Panama for 36 years in various sectors ranging from promoting sustainable agriculture to teaching English and life skills to youth and community environmental conservation. The Water, Sanitation and Hygiene (WASH) program, formally known as Environmental Health, serves many roles in their communities of work ranging from rehabilitating and/or constructing latrines to training local community members on water borne diseases and illnesses, to strengthening water committees to better protect their water resources (Peace Corps, 2018). One of the areas in which they have also often worked in is the construction and/or rehabilitation of water systems. The volunteers of this sector come from various educational backgrounds, including engineers and non-engineers. Most volunteers that work in the construction and rehabilitation of water distribution systems work with gravity fed water distribution systems, otherwise known as aqueducts, since Panama's mountainous geography, especially in remote areas, allows for easy water delivery with no mechanical energy.

The Master's International program was a program developed in 1987 with the goal of pairing graduate students with advanced and specific skills to opportunities in the Peace Corps that aligned with those skills (Mihelcic et al, 2006; Mihelcic, 2010; Manser et al., 2015). Panama has seen several Master's International students as volunteers across various sectors. Many of these students have provided thoughtful insight into the state of national water supply and service in Panama. From optimizing in-line chlorinators to disinfect water (Orner, 2011; Orner et al., 2017), to researching the effects of pesticides from small scale agriculture on water quality (Watson 2014), and assessing embodied energy of rainwater harvesting systems (Green, 2011), Peace Corps Panama Master's International volunteers have contributed to the investigation and improvement of local rural water sources and systems.

Michelle Roy, another Master's International Panama Peace Corps Volunteer (PCV) most recently completed a thesis titled *Investigation of Future Flow Reducer Sizes in Houses Added to an Existing Gravity Flow Water System to Ensure its Sustainability* (Roy, 2017). That research focused on developing simple rules for community water committee members to understand how to size flow disks, PVC inserts designed to restrict flow at certain faucets in order to equalize flow in a community water system over varying elevations and distances. Roy utilized an available water system design software called Neatwork to initially design the system, including the orifices she used. In her results she determined that system designers should: 1) design a water system to account for locations where the community believes individuals may build homes in the future, and 2) leave behind a map of which clearly shows in which areas of the community certain sized flow reducers should be placed. She also developed a guide for future system designers to teach the community and the water system committee members how to properly incorporate and maintain flow reducers in a water distribution system.

One important recommendation that Roy had for future research was to compare the results of the Neatwork model, a program utilized to aide in design and simulate gravity fed water distribution systems, to field measurements. This was because she assumed in her research that the model was accurate. She also recommended measuring flow at various houses simultaneously and modeling the same combination of open faucets at those houses on Neatwork. She recommends varying the percent of faucets open as well as varying the tank outlet height in Neatwork to get a more robust view of comparability between the field and the model.

1.3 Motivation and Research Objectives

The work of Roy (2017) provides interesting insight into the intricacies of designing a rural gravity fed water distribution system based on the results that a computer program provides. These results not only impact how the system designer chose to design and install the system at the moment, but potentially the way that the system is modified in the future to ensure sustainability. If Neatwork had not provided reasonably accurate results, it is possible that her work to more sustainably and accurately map the location and sizing of future flow reducers in Santa Cruz, Cocle, would be inaccurate, despite her capacity and skill in using the program and understanding of the way that flow reducers and pipe sizing works.

While based on well-established hydraulic principles, the Neatwork program has not seen published work that compares its program's results to a water distribution system in the field, installed primarily by the community. This type of comparison will be beneficial to the developers of Neatwork, who have the capacity to continue to enhance the program in newer versions, and it will also have the potential to benefit its users who work in remote areas and may not always have the tools or knowledge accessible to them outside of an open source program like Neatwork to make sound adjustments regarding their water distribution designs.

Accordingly, considering the gap that exists in verifying Neatwork against field data, this thesis has the following objectives:

1. Compare the flow measured at faucets in a rural gravity fed water distribution with estimated flow results produced in the program Neatwork to determine if the program produces accurate results under default Neatwork condition of 40% faucets open.
2. If the flows are found not to be comparable, use variations in the percent of open faucets to determine the effect that the percent of faucets open in a community has on the accuracy of Neatwork.
3. Verify that the flow at the designated faucet falls between the estimated flows from Neatwork for two scenarios: water tank height at the tank outlet and water tank height at the overflow.

The hope is that this research will inform Neatwork developers of future modifications they may be interested in making to the program, to improve its accuracy and suitability for users working in the developing world. This could be inherent changes to the way the program is designed or in the form of updated guides and manuals stating any limitations or the level of accuracy of the model that has been found in this research.

In Chapter 2 the author will summarize the important components of a gravity fed water distribution system as well as hydraulic principles necessary to understand piped gravity flow. She will also discuss what resources currently exist to model gravity fed water distribution systems, and go into detail on how the Neatwork program is structured. Chapter 3 will detail the materials and methods used to measure flow in the field as well as to produce the Neatwork estimations of flow. In chapter 4 the author will present the results of the research and provide a discussion for what the results show. Finally, in Chapter 5, the author draws conclusions regarding her objectives established in Chapter 1 and how this can be informative to the Neatwork program. She also discusses the potential for future work based on this research.

CHAPTER 2. LITERATURE REVIEW

2.1 Hydraulic Principles of Water Distribution

Before working on the design of any water distribution system, one must first have a basic of knowledge of the area where the system will be installed to appropriately apply fundamental hydraulic principles to establish a design. First, a surveyor must survey the area where the system will likely exist. The surveyor(s) will measure lengths and elevation changes between these lengths from the water source, to the tank, and ultimately to each house where a tap will be built.

After this process, the next step would be to determine pipe sizes by using the Darcy-Weisbach equation (Houghtalen et al, 2010).

$$h_f = f \frac{L}{D} \frac{V^2}{2g} \qquad (1)$$

In Equation 1,

h_f = friction head loss (m), f= friction factor (unitless),

L= pipe length (m),

V= mean velocity (m/s),

D= pipe diameter (m), and

g= gravity (m/s^2)

A friction factor, f, would be assumed depending on the pipe material and its age, while allowable headloss and length the pipe needs to travel are obtained from topographical data collected in the field and velocity determined by measured or estimated water demand. After solving for diameter, one would verify the above calculation using the Swamee-Jain equation (Houghtalen et al, 2010):

$$f = \frac{0.25}{\left[\log\left(\frac{e/_D}{3.7} + \frac{5.74}{N_R^{0.9}}\right)\right]^2} \qquad (2)$$

where,

f= friction factor,

N_R= Reynold's number, and

e/D= relative roughness

If the friction factor determined by Equation 2 is different than the assumed friction factor, one could re-estimate the friction factor, and re-calculate the pipe diameter using Equation (1) until the assumed and calculated friction factors match. Once the diameter is determined, a distribution system designer would round up the pipe size to the closest available commercial pipe diameter.

After calculating a pipe length, one could use Bernoulli's energy equation to ensure that energy requirements are satisfied. This is important to ensure water will arrive at all points throughout the system and also to ensure that, due to low or negative pressures inside the pipes, suction or negative pressure will not contaminate the water in the pipes by drawing in foreign substances through cracks or holes (Mihelcic et al, 2009). Bernoulli's equation summarizes the major portions of energy in a piped flow system which are pressure, kinetic and potential energy (Houghtalen et al, 2010).

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + h_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + h_2 \qquad (3)$$

In Equation (3),

$P_{1,2}$ = pressures are section 1 and 2 respectively (Pa)

$V_{1,\,2}$ = velocities in section 1 and 2 respectively (m/s)

$h_{1,2}$= elevations of point 1 and point 2 respectively, above a horizontal datum line (m)

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

One can further adapt Bernoulli's equation to include energy gains from pumps and various minor energy losses from components such as valves, tees, and elbows. More information on how to calculate minor losses for various components can be found in hydraulic/fluid mechanics related text (e.g., Houghtalen, 2010). One of these head losses that is of interest to water system designers in a rural developing world setting may be the friction loss through an orifice. The addition of an orifice directly upstream of the faucets of a water distribution system allows for flow to be constricted individually at every household, depending on the size of the hole created in the orifice fixture. The size of the orifice will depend on the desired head loss at a home which is dependent on the distance and elevation of the home from the water storage tank. With the installation of orifices there is a corresponding head loss through the orifice. The head loss through an orifice may be calculated from the following equation (Houghtalen 2010)[1]:

$$Q = C_d A \sqrt{2gh} \qquad (4)$$

where,[1]

Q= flow (m^3/s)

C_d= coefficient of discharge,

A= cross-sectional area (m^2), and

h= head loss through orifice (m)

---

[1] It should be noted that the Neatwork program assumes a different equation for orifice for a headloss. This equation is the following:

$$\delta h = -\theta \frac{\emptyset^2}{d^4}$$

where,

-(δh) = head loss across the orifice,
ϕ = flow rate (m^3/s)
d = diameter of the orifice in meters
θ = orifice coefficient

Rearranging equation (4) for headloss gives:

$$h = \frac{Q^2}{C_d^2 A^2 2g} \qquad (5)$$

Use of the Hydraulic Grade Line (HGL) allows one to visually understand the elevation head and pressure head in the system. The HGL is created by summing the elevation term (z) and pressure term (p/γ) in equation three over the course of the system. In order to create this HGL, one could easily start at the most upstream part of the system and subtract head losses as they traveled along the system such as inlets, valves, and connections. An example of this can be seen in Figure 1.

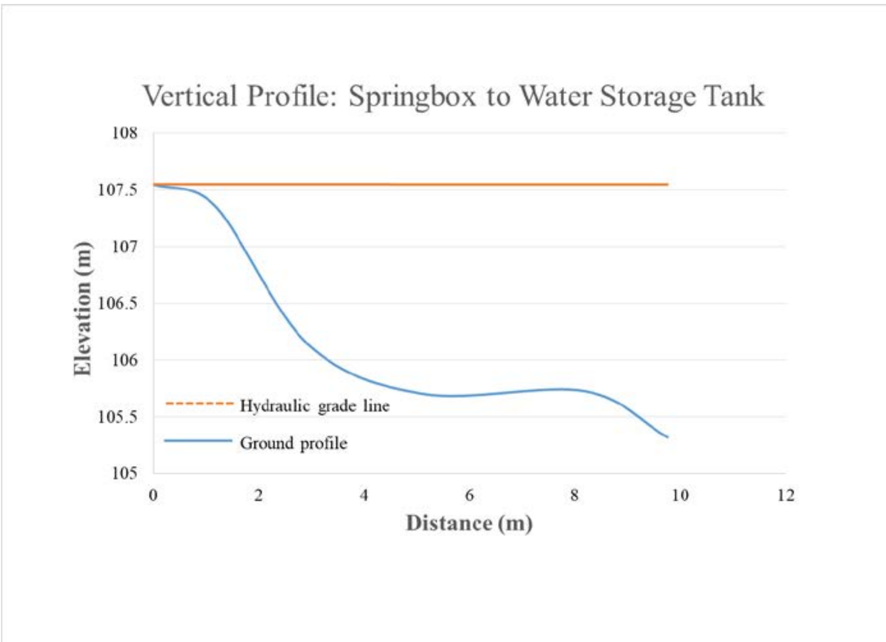

Figure 1. Example of a hydraulic grade line (HGL) over the distance between a water source and water storage tank.

2.2 Gravity Fed Water Distribution Systems

One of the ways to reduce the barriers to access to improved water worldwide is using piped systems. In many rural areas where mechanical energy is inaccessible or unfeasible to obtain, a piped, gravity fed water distribution system can be a reasonably affordable option to reaching the goal of providing access to safe water. Highly dependent on the topography of the region, a gravity fed water distribution system has the potential to provide water directly to the source of demand, in people's homes, schools or other points of gathering. These systems are typically community managed and methods have been developed to assess the sustainability of such systems (Suzuki, 2010; Schweitzer, 2009; Schweitzer, 2012).

The most essential parts of a gravity fed water distribution system are a water source that is typically a spring or a river (Figure 2), conduction line, storage tank (Figure 3), distribution line and tap stands (Figure 4). The distribution line occurs downstream of the water storage tank and may use branched or looped networks. Branched networks allow for the water to travel only one path, while in a looped network, water may arrive at a tap through various paths. Looped networks are more difficult to design and predict flow rate and pressure throughout the system, but offer the added advantage of possibly providing service downstream even if there is damage upstream (Mihelcic 2009).

Figure 2. Example of a low-profile spring catchment which serves to protect a natural spring and deliver water to a water storage tank.

Figure 3. Typical water storage tank (9000 L) in rural Panama.

Figure 4. Example of a tap stand in a rural setting.

There should be enough pressure, otherwise known as head, between the source and the tank so that the water can overcome any friction and minor losses in the transmission line. This is also true for piping between the tank and the faucets.

Many gravity-fed water distribution systems require additional specialized components to overcome potential challenges to water delivery. For example, break-pressure tanks may be required to overcome large gains in head to prevent pipe ruptures from excessive pressure, cleanout or air release valves may be used to prevent sediment or air blockage in pipes, settling tanks or filter systems may be included for water sources with substantial sediment (such as creeks or rivers). Furthermore, a community is often encouraged to incorporate some sort of disinfection technique, such as a chlorinator to increase the quality of the drinking water (Orner, 2011; Orner et al, 2017).

One of the many advantages to a system as described above, are the simple maintenance techniques and materials needed for future work and improvements. Since there are no mechanical or electrical components to this system, the most complex issues a community will face may be damages to pipe, tank or clogged pipes and valves. The process for fixing these can be as simple as learning how to cut and glue PVC pieces together.

2.3 Gravity Fed Water Distribution Design Tools

There have been several attempts at creating tools that will allow development workers to design water distribution systems using sound technical skills, appropriate technology and at a cost-efficient price. While most of these have a similar aim, the aspects that they choose to prioritize are unique to one another.

One example of such a tool is spreadsheet and guide developed by a Returned Peace Corps Volunteer (RPCV) and former Master's International graduate student (Reents, 2003). Reents uses excel as the platform for users to input topography data from an abney level to design a conduction line and/or a distribution line and useful calculations for tank sizing. Because this tool's platform is Microsoft Excel, it provides the benefit of being adaptable to the user who may choose to adjust equations or figures in the tool. There are also elements of cost estimating that may be useful for a user on a budget. One of its shortfalls may be the limited piping material available, as PVC and galvanized iron (GI) are the only two choices. Reents' spreadsheet however is not intended for the design of looped networks, but rather, for branched networks. This will likely not affect a development worker in a rural setting as looped networks are not common in such contexts.

Another program that can be used for the design of water distribution, by gravity or by pump, is EPANET (US EPA, 2018). EPANET is a program distributed by the USEPA to model water distribution systems in pressurized pipe systems while also providing information on the quality of the water throughout the system. EPANET has a user-friendly interface that makes it easy for non-engineers to decide what pipe diameters and type to be used, where to install tanks, valves and pumps, and calculates various values of interest such as pressure head at nodes, flows in pipes, average water quality in the pipes, and more. Unfortunately, EPANET assumes that all pipes are pressurized and there are no air blocks, which is unlikely a reality in water systems in a developing world setting. EPANET does have the benefit that data can be inputted from GIS, AutoCAD or google earth.

GOODwater is another tool developed by a Master's International student, specifically designed to help development workers in rural areas design and implement gravity fed water distribution systems (Good, 2008). GOODwater allows the user to design a branched system and provides information about pipe sizing and optimization for cost efficiency. It improves upon cost estimation by allowing the user to enter data about other systems in the area so that the program can develop a baseline for costs. One of the unique aspects to this program is its interest in sustainability of the design. It encourages the user to consider aspects such as: socio-cultural respect, community participation, political cohesion and economic and environmental sustainability. One of the downsides of GOODwater is its simplicity for those users that are interested in looped systems, systems using pumps, consideration of valves, break pressure tanks, the limited availability of pipe diameters and overall components to the system.

The program of interest to the author, Neatwork (Agua para la Vida, 2018), is another tool with similar objectives as the previously mentioned technologies. It is yet another computer program designed to deal specifically with gravity fed water distribution systems, with capabilities to work with the design of only the distribution line. The conduction line and tank are aspects of Neatwork that are currently incorporated into the program. Table 1 provides a summary of the capabilities and features of the four-aforementioned water distribution modelling programs.

Table 1. Summary of programs developed to aide in design of water distribution systems applicable in developing world setting.

	Neatwork	EPANet	GOODWater	Reents
Pipe type and diameter to use • For Conduction line • For Distribution line	No Yes	Yes Yes	Yes Yes	Yes Yes
Looped Networking	Yes but with limitations	Yes	No	No
Cost Analysis/Optimization	Yes	Yes but with limitations	Yes	No
Scheduling	No	No	Yes	No
Tank Sizing	No	No	Yes	Yes
Orifices	Yes	No	No	No
Friction Losses for various fittings	Yes but with limitations	Yes	Unknown	No
Water Quality	No	Yes	No	No
Visual depiction of network • Profile view • Plan view	No Yes	No Yes	Yes No	Yes No
Ability to incorporate pumps	No	Yes	No	No
Ability to simulate various scenarios	Yes	Yes	No	No
Break Pressure Tank Location	No	No	No	Unknown
Intended for developing world use	Yes	No	Yes	Yes

The aforementioned programs are free of charge and designed for use by any professional working in the development world, and not only engineers or people of the technical field. They all have the ability and history of being used for modeling of water distribution systems in developing world contexts. Other, more advanced, water distribution modeling exists for larger and more complex systems. Some of these programs include: WaterCAD, WaterGEMs, InfoWater, and KY Pipe. Because of the robust nature of these programs, they all come at varying costs to the user.

The author chooses to carry out this research with an emphasis on the Neatwork program for a variety of reasons, principally being that it is the most commonly used method to design rural gravity fed water systems amongst Peace Corps volunteers in Panama. Because it has wide use amongst these users, it has fostered a community of experienced in-person technical support that other programs in Table 1 would not be able to provide. The ability to easily incorporate topographic information in a form that Neatwork understands, whether it be due to the programs ease of use or the common knowledge among Peace Corps volunteers of how to adapt data points to this program, allows for relatively simple data entry. Creating multiple designs and executing multiple simulations are also easily repeated processes for Peace Corps Panama volunteers due to the interface and knowledge in the Peace Corps community. Many Peace Corps Panama water, sanitation and hygiene volunteers work in areas lacking access to improved water sources and many also do not have amenities such as internet or electricity. Therefore, the time required to become comfortable with a program via internet tools or resources are most useful when kept to a minimum for water system design.

2.4 Calibration of Water Distribution Models with Field Data

As previously mentioned, there are several tools available to aid in water distribution design. Some researchers have published work to validate the accuracy of these programs, such as with EPANET. The following are a handful of these key studies, which are most closely related to validating these programs with in-field data. It should be noted that these studies took place in a developed setting, with the exception of the work of Briana Drake (2015), which was research done as part of the requirements for a Master's program.

In a study done by Monteiro et al (2014), they validate the EPANET Multi-Species Extension (MSX) chlorine decay model against chlorine data produced in the field, at difference points along a water distribution system using the water distribution system in Algarve, Portugal. They find that the differences between measured and modeled chlorine concentration increased as they measured further downstream from the water treatment plant. Overall, though, they did determine that the model was within measurement uncertainty, with an average relative error of 3%.

Another study by the USEPA National Homeland Security Research Center (NHSRC) seeks to understand the accuracy of the EPANET-RTX (the EPANET "Real Time eXtension") by performing a field scale evaluation of a real-time hydraulic and water quality model of the Northern Kentucky Water District (NKWD) (NHSRC, 2014). The field portion of this study was conducted over a one-week evaluation period and EPANET-RTX data was compared to operational data and calcium chloride tracer data for the NKWD system that serves nearly 300,000 people. The study found that EPANET-RTX is successful in processing supervisory control and data acquisition (SCADA) for hydraulic modeling and highlights its scalability for any water system with suitable infrastructure network model and sufficient SCADA datasets (NHRSC, 2014).

Another relevant study that focuses on the implementation of flow reducing disks and the effectiveness of solar powered water supply make some comparison in a rural community in Guyabo, Panama uses Neatwork as the modeling platform (Drake, 2015). Drake measured flow at taps in the community of Guyabo and compared it to Neatwork simulated flow to perform a sensitivity analysis on the orifice coefficient value (θ), which Neatwork defaults as θ=0.59. Drake performed these field measurements using three faucets with five-gallon buckets in the community, and using whistles as markers for when to start and stop the opening/closing of faucets and measurement. The time itself was collected by an individual that was not filling the bucket. Drake finds that using a θ=0.68 increased the accuracy of the model.

2.5 Neatwork Model

Because the most commonly used tool to design water distribution systems among Peace Corps volunteers in Panama is Neatwork, the author will focus on the details surrounding the fundamentals and use of Neatwork. An understanding of the Neatwork platform, parameters used, data inputted and outputted is essential in capturing the objectives, methods and results of this research.

The creators of Neatwork describe the program as "A decision support program for the design of gravity water distribution networks". This program, developed by Agua Para la Vida, a non-profit working in rural water development based in Nicaragua, was developed so that development workers of all academic backgrounds could have a tool to develop a design for a functioning water distribution system at a minimal cost. Neatwork states that its goal is to find a compromise between being cost efficient while ensuring that the flow at each faucet stay within bounds set by the user.

The sections that follow provide a summary of the Neatwork way of developing a design and running a simulation in Neatwork. In order to effectively use Neatwork, it is important that the user understand how and why Neatwork asks the user to provide certain information, even when there are default options to choose from. Because Neatwork uses the term “faucet” more and other literature that is reference in this thesis may use “tap” it should be noted that the word “tap” and “faucet” are used interchangeably in this thesis.

2.5.1 Topography

To create a design and further produce a simulation, Neatwork requires the user to input topographical data in a simple format that details node connections, segment lengths, heights between nodes, and identifiers for the nodes (tank, point, or tap). This can easily be done in excel with the appropriate format, and later copied and pasted into Neatwork.

2.5.2 Design Input

Once a topography is created, a design can be created based on this topography. The following subsections provide a summary of the information required from the user by Neatwork in order to create a suitable design.

2.5.2.1 Hardware

Neatwork calls from two databases, one for pipe diameters and one from orifice sizes, to allow the user to select the sizes they wish to be included as options for the final design. This may be modified to add pipes and orifices that are not included, but editing the database itself. Pipe diameters specify nominal diameter, standard dimension ratio (SDR), estimated cost and maximum pressure rating.

2.5.2.2 Parameters

In this tab, the user must carefully select values that will shape the design of the system. Default values automatically appear in all of the following entry boxes for the following parameters. Below is a brief summary of these parameters.

- Fraction of faucets opens: This is based on the average peak use in each individual community, and is the fraction that the program uses to design the system. It can be adjusted for specific simulations after the design phase to see how it performs. Neatwork uses a default of 40% taps open for their, which can be changed by the user.
- Service quality: This value helps create a balance between the favorable outcome of faucets getting sufficient flow under many circumstances, with the reality that a higher functioning water distribution system comes at a greater economic cost. As neatwork states "the higher this value, the more generous the assignation of the diameters of intermediate pipes between initial and the final segments and so for a fixed flow the higher the average flow rate in the faucets in general". The user should adjust this value as they simulate the flow in order to optimize the functionality and, simultaneously, the cost of the system. While the current Neatwork manual recommends a start value of 0.6, the author, through personal communication with the creators of Neatwork, has found that a service quality of 0.65 to be a more appropriate initial value. (According to e-mail correspondence with creator Gilles Corcos on January 16th, 2018).
- Target flow: This is the average flow that the user hopes to obtain.

- Limit of the budget: Here the user can inform the program of any budget constraints to better select piping to meet this limit and satisfy system requirements.
- Water temperature: Set to a default value of 20℃. Water temperature is used to determine water viscosity. It can be changed for regions that may have drastically varying water temperatures.
- Pipe commercial length.
- Orifice coefficient: This constant helps establish a relationship between orifice head loss, flow rate through it and orifice diameter. Neatwork notes that the coefficient may vary according to the geometry of the orifice, which in the case of this work, could be significant considering the method for creating orifices used in the field, which will later be discussed. The default Neatwork recommendation is 0.59.
- Faucet coefficient: Dependent on the type of faucet used. If the value is unknown Neatwork provides a way to calculate this value. The process for this can be found in Appendix E of the Neatwork manual.

2.5.2.3 Constraints

For users that are working to modify or optimize an already existing system, this feature allows them to inform Neatwork of which segments already have a pipe diameter designation. The program gives the user the option to choose a specific segment and whether the user would like to keep the diameter greater than, less than, equal to, or both diameters (for segments cut up in series) equal to a user determined diameter from the diameter database.

2.5.2.4 Load Factor

The load factor is a result of the service quality. For segments leading to a single node, the load factor will be one. For segments with several faucets downstream, the load factor is computer. A higher service quality will decrease the load factor in these cases.

2.5.3 Design Menu

After a design has been completed and saved, Neatwork allow the user to view a report of the design in HTML that details the orifice sizes selected per faucet and the pipe diameter and type recommended for each segment. The orifice sizes are presented in two columns: “Ideal orifice” and “Commercial Orifice”, which ideal being the calculated orifice and commercial being the closest size that could be commercially found. Neatwork allows for a segment in the system to be allowed more than one diameter size if it is found to be ideal, which is why there are two columns for length and diameter under arc list. “Length1” suggests that the first “x” meters be assigned the pipe type under the “Diam1” column while the “Length2” and “Diam2” refer to the downstream portion of the segment.

2.5.4 Simulation Inputs

To understand how the flows will change under varying conditions of open/closed faucets, the user must familiarize themselves with the simulation component of Neatwork. The simulation module will compute flow at the branches for a randomized combination of open/closed faucets. The user defined parameters for the simulation component are as follows:

1. Number of simulations: this is normally anywhere between 100 and 500 simulations depending on what the user is interested in producing and the capacity of the computer being used.

2. Fraction of open faucets: This is not necessarily the same number that was used for design. The user should start with the same value and vary it as they create new simulations to see how the outcome is affected.
3. Critical flows: this value allows Neatwork to display when the desired outcome was outside of these bounds but does not actually affect the simulation itself.
4. Target flow: The same value chosen for the design, which also does not affect the simulation.
5. Type of orifices: The user can choose to between ideal or commercial orifices. As mentioned previously, ideal is the size calculated by Neatwork and commercial is the closest size that might realistically be available to the user.
6. Type of simulation: The user may decide the standard/default Monte-Carlo sampling method, individual faucets which only allows one faucet open at a time, or user-defined where the user can decide which combination of faucets will be allowed to open.

2.5.5 Simulation Output

After running a simulation, Neatwork will produce four types of data: 1) flows at faucets, 2) percentiles of maximum flow at faucets for varying lowest percentiles (10%, 25%, 50%, 75% and 90%), 3) average and maximum speed in individual pipe segments and 4) minimum, average and maximum pressures at each node.

Flows at faucets shows the user what the minimum, maximum and average flow was at each faucet and how many times that faucet was open. It will also inform a user about the percent variability of the flows for a given faucet as well as what percentage of times the flow was outside of the user defined flow bounds. Neatwork will also show the number of “failures”, or when there was no flow when open, for each faucet.

2.5.6 Fine Tuning a Neatwork Design

After creating the design and running the simulation for the first time, the user can determine if they are “satisfied” with the designed system. For example, the user may find that while the flows at the faucets are all satisfactory (within created bounds) that the expense of using the recommended pipe diameters and lengths could be further reduced. In this case it would be appropriate to decrease the service quality factor. Perhaps the user believes that the flows are too low, yet does not want to increase pipe sizes. In this case it might be useful to limit the orifice sizes to larger diameters.

There are various adjustments that can be made to optimize a system that will satisfy the user’s needs. It is the responsibility of the user to understand these tools that the program has to offer and manually adjust as they work towards the ideal system.

CHAPTER 3. MATERIALS AND METHODS

To understand whether Neatwork produces accurate flow data, it was necessary to produce a simulation of Neatwork in the program which, as closely as possible, corresponded to a simulation in the context of an actual gravity fed water distribution system in a developing world setting. This chapter provides details on how the author addressed this, both in the field and in the Neatwork design software.

3.1 In-Field Data Collection

3.1.1 Data Collection Location

In order to compare actual in-field flows with Neatwork produced flows, Neatwork conditions needed to be mimicked in a physical environment. The site chosen for this portion of data collection was the community of Alto Nube Abajo, in the Comarca Ngöbe Bugle, Panama. This community of about 100 men, women and children, was the Peace Corps community of the author between 2015 and 2017. The rainy months of September and October were chosen for data collection so that it was more likely that the water storage tank would be full.

The existing water distribution system was completed about four months prior to the start of the flow measurements. Prior to system design, the author, previous Peace Corps volunteers, and the community carried out topographical land surveying using the simple process of water leveling- where two ends of clear flexible tubing that are filled with water are fixed on to marked lengths of PVC. The change in water level observed in the clear tubing, easy to see because of the marked PVC, was recorded as well as the distance traveled.

The current water collection, storage, and distribution system was designed by the author, using Neatwork in conjunction with excel and community input to determine pipe sizes, pipe lengths, placement of air release valves and sediment clean out valves, as well as water storage tank location. The system source is a natural spring, protected by a low-profile spring box. The low-profile spring box consists of a concrete wall built on an impermeable layer of bedrock, filled with clean rocks, graded in decreasing size from the ground to the wall height so that water can easily pass through, while still supporting a three-inch slab on top of the rocks. The spring catchment has three breather tubes made of ¾" PVC perforated with hot nails, an overflow pipe, cleanout pipe, and access hatch for cleaning. The water distribution system includes 20 taps with a conduction line of 135 meters and distribution line of 1,681 meters. All pipes are PVC with varying standard dimension ratios (SDR) depending on availability and the pressure the pipe needs to withstand. A detailed description of pipe lengths, SDR and sizes used for this water system for the distribution line is provided in Table 2.

Table 2. Pipe diameter with corresponding pipe lengths and standard dimension ratio (SDR) for distribution line piping.

Pipe Diameter (in)	SDR	Length (m)
2	26	73.12
1 1/2	26	25.39
1	26	189.15
3/4	21	491.52
1/2	13.5	901.97

3.1.2 Orifice Installation

Orifices, otherwise known as flow discs or flow reducers, were installed into the system to help equalize flow at the houses. The orifices are needed in order to sustain the water distribution over varying seasons and therefore, varying levels of water supply. Houses farther downhill and/or closer to the tank will receive smaller orifices, resulting in a greater head loss while houses closer to the tank in distance and/or elevation, will require a large nail sized orifice or none at all. The orifices were made by using the most locally appropriate method of heating nails of various sizes to make holes in small, flattened pieces of PVC. The easiest way to make the disk is cutting an at least 2” diameter PVC section of pipe (length depending on how many flow disks are to be made) lengthwise and then heating this in hot oil enough to make it malleable and flatten it with an object such as a glass jar. After the PVC has been flattened, a heated ¾” nipple is used to make the plastic diaphragm that, after being filed, fits into a ½” PVC union. Before inserting the disk into the union, a hole is made with a hot nail whose size is dependent on the orifice requirement of the tap where it will be installed. Four sizes of nails were used and are identified by their nail length, since this is the most widely understood method of identifying nails among community members and hardware store owners, as opposed to their diameter. The nail lengths, corresponding diameters and the house in which they were installed can be found in Table 3..

Figure 5. Setup for creating PVC cutouts to make flow disk. Pliers are used to hold the hot pipe nipple over an open flame and is then immediately used to punch a hole out of flattened PVC.

Table 3. Available nail lengths, corresponding orifice sizes, and orifice house designation.

House	Orifice Size (mm)	Nail length (in)
Lidia	5.05	6
Micaela	5.05	6
Ernesto	5.05	6
Julia	5.05	6
Cristina	5.05	6
Minsdu	5.05	6
Rulfina	5.05	6
Benita	5.05	6
Choli	4.00	3
Toman	4.00	3
Abundio	4.75	4
Tito	4.00	3
Alexis	3.85	2.5
Chidtoj	3.85	2.5
Federico	3.85	2.5
Virginia	4.00	3
Martina	3.85	2.5
Roberto	3.85	2.5
Anastasio	3.85	2.5
Augustin	3.85	2.5

Figure 6. Example of flow disk placed inside PVC union ready for installation.

Roy (2017) recommends using a drill and drill bit to be able to make these flow discs more accurately, but unfortunately this option was not available to the author or the people of the community due to lack of electrical energy and power tools. Accordingly, the author measured the orifice holes installed for this research in four directions using a caliper and averaged the values to come up with a diameter. Because of the imperfect circles made by the nails, some orifice sizes may not be exactly the size that was used in Neatwork.

3.1.3 Measurement Variations

Ten combinations of flow measurements were carried out, varying the percent of faucets open from 10-100% with ten percent increments (10%, 20%, 30%…).

Changing the amount of taps open, versus maintaining all or a select combination of open/closed taps simply allowed the author to compare field measurements over various combinations of open/closed faucets to Neatwork data. Considering that the change in design variables in Neatwork was impossible to vary because of the permanent nature of the water distribution system in the field, it was important to vary a simulation parameter in the Neatwork program, to analyze consistency over various iterations of results.

3.1.4 Choosing How to Vary Selected Taps Open

The combinations of open/closed taps were based on location of a particular tap with regards to its distance from the water storage tank. The first measurement of flow at the faucets was made with all taps fully open, and decreasing by two taps for each subsequent measurement. For example, the first measurement included all 20 taps of the community system open, the second trial included 18 with two of the furthest taps from the water storage tank being excluded (all taps minus taps 19 and 20), and the following measurement of sixteen taps open excluded two of the succeeding furthest taps from the water storage tank (all taps minus taps 19, 20, 13 and 14). Figure

7 illustrates the location of the various faucets relative to one another and the distribution line of the system.

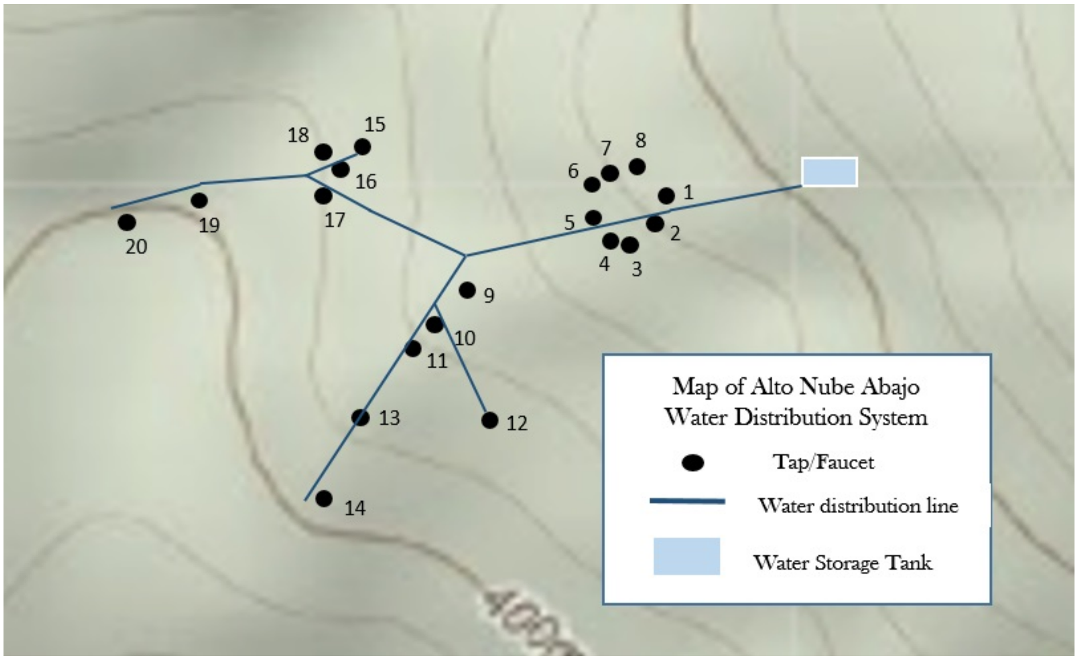

Figure 7. Map of Alto Nube Abajo (Panama) water distribution.

The combinations were done in this way to avoid working with the furthest taps more than necessary. The further away the taps, the more difficult it was to clearly send the signal to open and close the taps at the appropriate time. This is because the signal to open or close a tap was communicated using whistles that reached a limited distance. Therefore, to reduce human error, the taps per measurement were reduced according to the distance from the starting point, which were the houses closest to the tank and also, where the signal to open/close taps started. The tradeoff with this method, may be seen in the trials involving only the last 8 taps, which happen to have the least amount of variation in space and elevation change. This may make it difficult to compare flow between faucets, without contributing results to error in topographical measurement. Table 4 demonstrates the combinations of faucets open/closed used in the field for measurements of 10-100% while Figures 8 and 9 show the elevation profile of the system

Table 4. Combination of open taps for 10-100% open faucets in-field. Numbers in left column correspond to faucet numbers in Figure 7.

		Number of Taps Open									
No. on Map	Household	20	18	16	14	12	10	8	6	4	2
3	Lidia	X	X	X	X	X	X	X	X	X	X
2	Micaela	X	X	X	X	X	X	X	X	X	X
4	Ernesto	X	X	X	X	X	X	X	X	X	
6	Julia	X	X	X	X	X	X	X	X	X	
1	Cristina	X	X	X	X	X	X	X	X		
5	Minsdu	X	X	X	X	X	X	X	X		
8	Rulfina	X	X	X	X	X	X	X			
7	Benita	X	X	X	X	X	X	X			
9	Choli	X	X	X	X	X	X				
10	Toman	X	X	X	X	X	X				
15	Abundio	X	X	X	X	X					
16	Tito	X	X	X	X	X					
11	Alexis	X	X	X	X						
12	Chidtoj	X	X	X	X						
17	Federico	X	X	X							
18	Virginia	X	X	X							
13	Martina	X	X								
14	Roberto	X	X								
19	Anastasio	X									
20	Augustin	X									

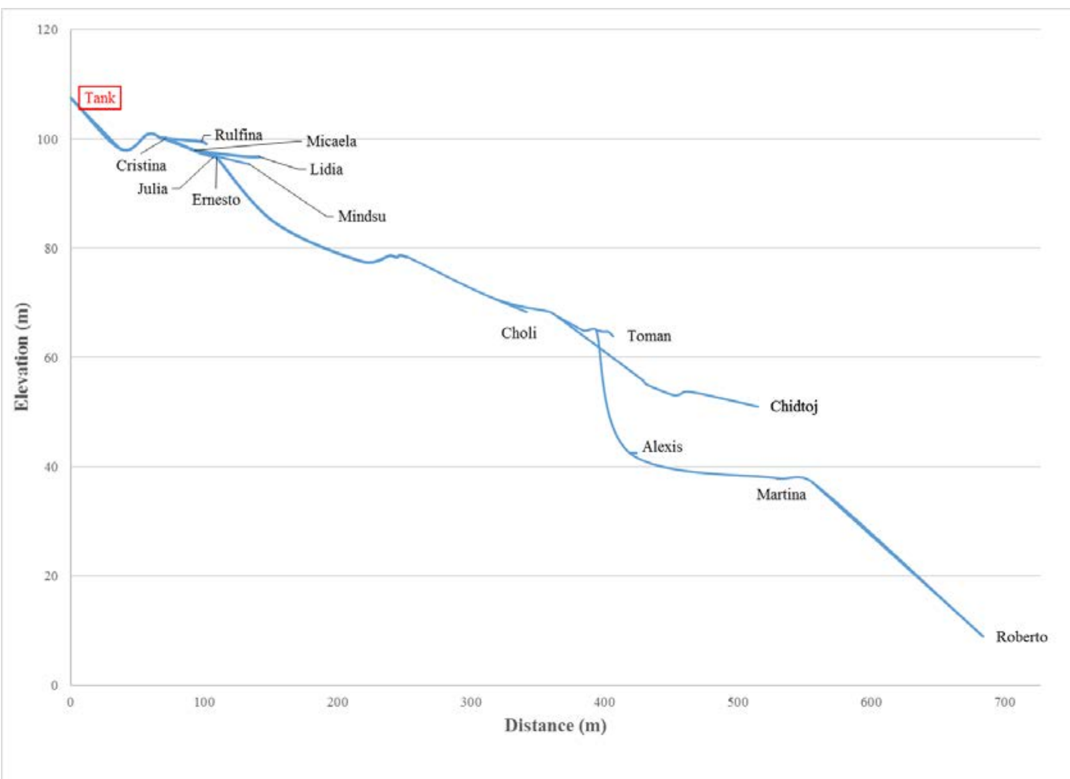

Figure 8. Elevation profile of Alto Nube Abajo water system from tank to Roberto's tap.

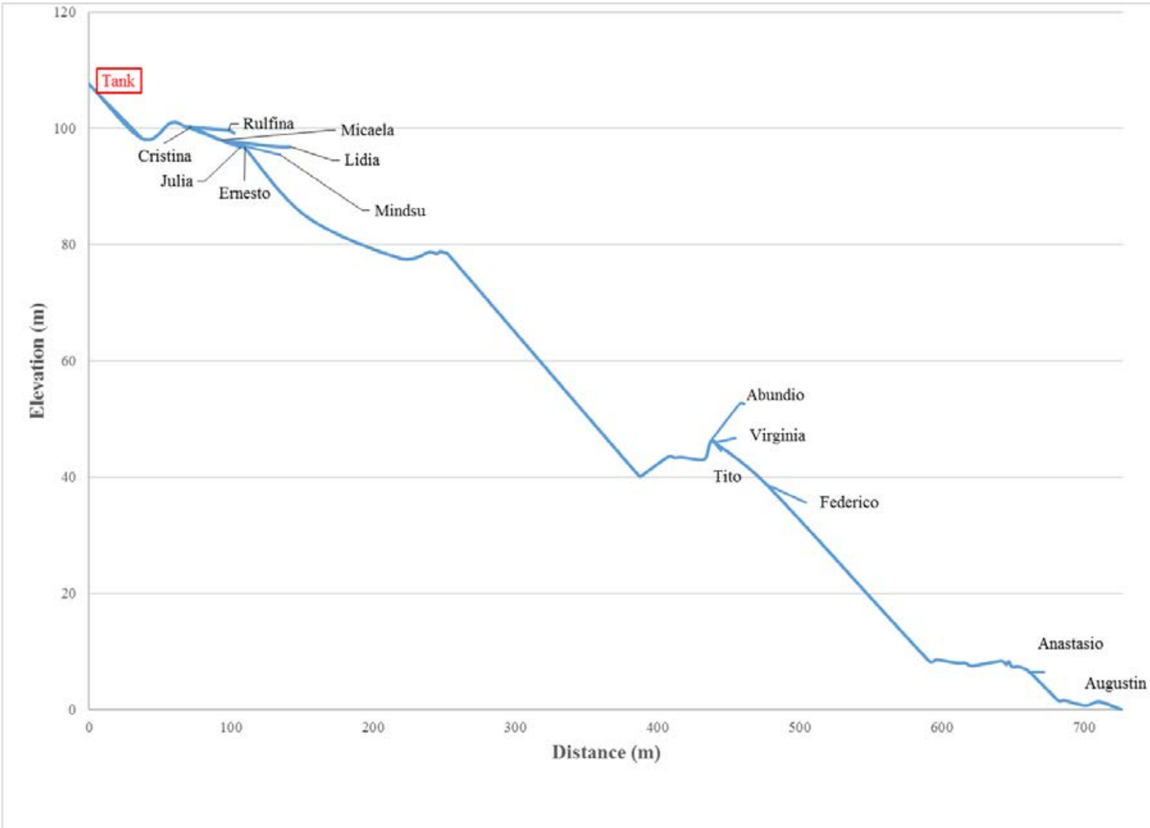

Figure 9. Elevation profile of Alto Nube Abajo water system from tank to Augustin's tap.

3.1.5 Volunteers

Volunteers were needed to measure the flow at taps at various households at the same time. These volunteers were members of the community, of all ages and education levels. Volunteers that made the flow measurements were primarily youth (ages 12-18) that had an interest in learning how to use a stopwatch. The author trained every individual on a one-on-one basis to teach them the process of measuring and recording flow and specifically, how to use a stopwatch.

3.1.6 Signaling the Start/End of Measurements

One of the most challenging steps of flow measurement was signaling to the designated houses when to open and close their faucets. In order to have accurate data, it was very important to know that when someone at, say, Lidia's tap was measuring the flow in their faucet, that the appropriate taps elsewhere were open as well, and not delayed. This became especially difficult considering the distances the noise needed to travel and physical barriers to noise travel such as areas of thick vegetation and flowing water bodies like creeks and rivers.

This signaling was done with a series of whistles. Prior to actual measurements, a handful of volunteers aided in blowing whistles at designated areas while the author moved along the water distribution line, stopping at every house to plan where and how many whistle blowers were needed. A minimum of five whistle blowers were needed to satisfy the need to signal the maximum combination of faucets (100% or 20 taps).

Volunteers were also needed for the actual measurements. The process of measuring included:

1. Being equipped with a five-gallon bucket, timer that measured up to one hundredth of a second, pen/pencil and data sheet.
2. Opening and closing the faucet to make sure the faucet was working and that the bucket captured all of the water. At homes with pressure great enough that water would spray and not be captured entirely by the five-gallon bucket, a second five-gallon bucket was used, flipped upside down as a surface to elevate the receiving bucket. This was done so that the receiving bucket was closer to the discharge and water would not escape.
3. Upon hearing the three consecutive blows of a whistle, the designated taps for a particular experiment were opened and each volunteer counted fifteen seconds to ensure that all other taps included in the measurement were open.
4. Once the fifteen seconds passed, volunteers simultaneously placed the five-gallon bucket under the stream of water and started the timer. In the event that an error occurred, such as the timer not starting and water already filling the bucket, or the bucket not being well

placed under the stream of water, the volunteers were asked to empty the contents of the bucket (always maintaining the faucet open) and start timing again when they were ready.

5. The volunteer would wait until the bucket was filled to the five-gallon line (a line marked on the inside of the bucket with a permanent marker) and then stop the time and record it on the data sheet.
6. The volunteer would continue to leave the faucet open, empty the bucket and do this 1 or 2 more times depending on time limitations (one faucet where flow rate was unusually low, only took time once per measurement). These 2-3 times were later averaged to create one time per house combination.
7. After the volunteer finished recording the 2 or 3 times, they would continue to leave the faucet open until another whistle blew, which was the signal to turn off their faucets.
8. This process was done for the measurements from 10-100% faucets open.

Figure 10. Author doing a review of steps to measure flow. In this photo she is demonstrating the need to wait fifteen seconds after fully opening the faucet upon the first whistle blow to place the bucket for measuring, as detailed in step three.

3.1.7 Notes on Field Measurements and Accuracy

While the method of collecting flow results in the field were consistent and practiced, it should be noted that there were apparent unforeseen outcomes during measurement, specifically in the case of Alexis's tap. Alexis, who resides neither the furthest or closest from the tank in elevation or distance, experienced the slowest times for filling a five-gallon bucket. For this reason, flow was only measured once for each variation of open taps where his tap was open (20, 18, 16 and 14 taps open) as can be noted in the raw field data in Appendix B1. The longest time to measure a five-gallon bucket at Alexis's tap was nearly 17 minutes when 18 taps were open while the second longest time to fill a receptacle of the same volume at a different tap was 7.9 minutes at Toman's tap for 20 total taps open in the system. This leads the author to believe there was a level of uncertainty in some of the field measurements, such as at Alexis's tap, that may affect results and this should be considered when interpreting the results of this work.

3.2 Neatwork Topography, Design and Simulation

3.2.1 Topography and Constraints

To simulate the system in Alto Nube Abajo in Neatwork, the survey data was inputted into the "Topography" component of Neatwork. In the "Design" component of Neatwork, the "Constraints" tab was used in order to insert the as-built design of the Alto Nube Abajo water distribution system. Since the constraints set for this design would constrain the entire system to an already established design (per what was installed in Alto Nube Abajo), the design parameters tab was left with default values since the constraints applied would override any design Neatwork would attempt to produce, with the exception of orifices.

Neatwork currently does not allow for orifice sizes to be applied as a constraint, but rather, chooses them for you. The user does have the control of limiting which orifice sizes Neatwork may choose from, which is what the author did (see Methods: Field measurements for orifice sizes). Table 5 provides the design parameters for all simulations run with Neatwork for this research (10-100% taps open and overflow versus outlet tank height). Refer to Appendix A for a complete list of the topography and constraints applied.

Table 5. Design parameters used in Neatwork for all simulations for this research including 10-100% taps open and overflow versus outlet tank height.

Design Parameters	
Start Design Parameters	
Fraction of Faucets Open	0.4
Service Quality	0.65
Target Flow (l/s)	0.2
Limit on Budget	1.00E+09
Physical Constraints	
Water Temperature (°C)	20
Pipe Commercial Lengths (m)	6
Advanced Parameters	
Orifice Coefficient	0.59
Faucet Coefficient	2.00E-08

3.2.2 Simulation

Once all "design" input variables were selected, the simulation could be run. Normally one would be interested in running various iterations of a simulation set to a certain percentage of faucets open to have a breadth of knowledge of the "real world" scenarios, where people open and close taps at random. In this case just one simulation was run as well as the "user defined" iteration setting, so that the configuration of faucets open or closed could be controlled to match the field conditions. The settings of ideal flow rate were left at default settings of 0.2 L/s with a minimum and maximum flow being 0.1 and 0.3 L/s, respectively, because we consider them to be reasonable. If a produced flow falls outside of this range, the simulation will flag it as falling out of the desired range of flow. If a faucet is shown to produce no flow when it is opened, Neatwork will flag it as "failed". When the type of simulation selected is "user defined", once these parameters are saved the user has the option to select the taps to be open during the simulation, which are the same as the in-field settings (See Table 4 from 3.1.4). Table 6 provides a list of the settings used for all simulations run for this research:

Table 6. Simulation parameters used in Neatwork for all simulations for this research including 10-100% taps open and overflow versus outlet tank height.

Simulation Parameters	
Number of simulations	1
Fraction of open faucets	-
Critical flows (l/s):	
low	0.1
high	0.3
Target Flow (l/s)	0.2
Orifices in use	commercial
Type of simulation	user defined

Upon simulation, various tables are produced by Neatwork such as percentiles of flow at faucet, speed of flow in pipes, node pressure, and perhaps the one of most interest, flow at individual faucets. An example of how Neatwork presents this information can be seen in Figure 10 which is an example of the simulation results window for a simulation run with topography from Alto Nube Abajo.

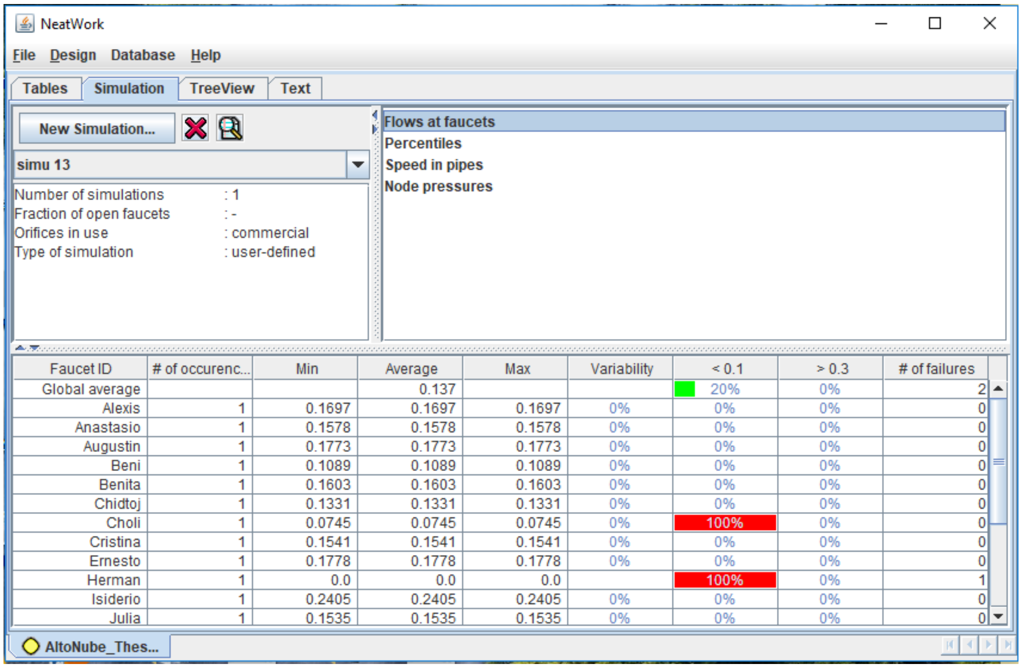

Figure 11. Example of Neatwork simulation results page showing flows at faucet for water distribution system.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Changes to Field and Simulation Comparisons

When the field measurements were performed, the orifice/flow discs were installed for the original Neatwork design where all design parameters were set to default, including the orifice coefficient (θ = 0.59). For this original design the water level height was also set at the default Neatwork setting (tank outlet = water level height). These original conditions were provided in Chapter 2. It was not until later in the study, after departure from the community, that the author became aware of a previous study that validated Neatwork by varying the orifice coefficient (Drake, 2015). With the intention of replicating this process of validating the orifice coefficient, the system was re-simulated under these new conditions.

Unfortunately for this new simulation, the program assigned some of the taps different orifice sizes than originally recommended and there is currently not a way in Neatwork to constrain a specific orifice size to a specific tap. Orifice sizes changed for various tap stands when the orifice coefficient was changed to the suggested values of 0.62 (recommended by Neatwork developers) and 0.68 (recommended by Briana Drake, 2015). For the simulations made for the scenario where 10% to 40% of the taps were set to be open in the field, orifice sizes did not change in Neatwork (for $\theta = 0.62\ or\ \theta = 0.68$), and therefore a comparison for these simulations was still considered suitable.

Similarly, this occurred for the simulation where all design parameters remained the same, yet the water level height in the storage tank was changed (see objective 3). Originally Neatwork assumes the conservative case where water level height (i.e. z = 0) is considered the tank outlet, found at the bottom of the tank. The water level height was changed to consider the case where the water tank is full and water level is at the tank's overflow, towards the top of the tank, in our case adding an additional 1.5 meters of head. Neatwork chooses the tank outlet as a conservative way to create the design and estimate flows, because it assumes no added pressure head from the water level in the tank. When modifying the topography to account for the pressure head from the added 1.5 m of water in the tank, the orifice sizes assigned to various taps also changed. The taps with changed orifice sizes affected all combinations of open taps except for the condition of 10% of faucets open, at the residences of Lidia and Micaela. For this reason a comparison between the field measurements and simulation for the two water level heights was made when only these two taps were open.

A summary of the comparisons of the field measurements that were made, along with any discrepancies in comparison, is provided in Table 7. All of the simulations carried out in Neatwork were constrained in the design for pipe size and pipe length for each pipe segment. All designs also chose orifice sizes from the list of available orifice sizes in Table 7.

Table 7. Summary of final comparisons made in Neatwork and field data

Comparison Type #	Field Condition	Simulated Conditions	Notes
1	10-100% taps open, each iteration changing by 10% increments	10-100% taps open at 10% increments • Topography: Tank height set at tank outlet (Neatwork Default) • Design: All design parameters set to Neatwork default	Total of 10 comparisons made, where all orifice sizes in Neatwork correspond with orifice sizes in the field. This condition summarizes results of objective 1 as well as objective 2.

Table 7. (Continued)

2	10% taps open (same results from 10% taps open in comparison type #1)	10% taps open • Topography: Tank height set at tank overflow • Design: All design parameters set to Neatwork default	Because of the topographical change, the subsequent design in Neatwork changed orifice sizes at select taps, while the field results maintained the same as in comparison type #1. This resulted in the iteration of only 10% of taps open for field and simulation to match exactly.
3	10-40% taps open (same results from comparison type #1)	10-40% taps open at 10% increments • Topography: Tank height set at tank outlet (Neatwork default) • Design: All design parameters set to default except orifice coefficient, which is set to 0.62	Because of the change in the design parameter, orifice coefficient, the Neatwork program changed orifice sizes at select taps, while the field results stayed the same as in comparison type #1. This results in iterations between 10 and 40% of taps open for field and simulation to match exactly
4	10-40% taps open (same results from comparison type #1)	10-40% taps open at 10% increments • Topography: Tank height set at tank outlet (Neatwork default) • Design: All design parameters set to default except orifice coefficient, which is set to 0.68	Because of the change in the design parameter, orifice coefficient, the Neatwork program changed orifice sizes at select taps, while the field results stayed the same as in comparison type #1. This results in iterations between 10 and 40% of taps open for field and simulation to match exactly

4.2 Results for Condition 1: 10-100% Taps Open

Table 8 below shows the in-field flow measurements against the neatwork simulated flows for all results from the condition 1 described in section 4.1.

Table 8. Flow results measured in the field and by Neatwork simulation program for varying number of open taps.

	Number of Taps Open																			
	20		18		16		14		12		10		8		6		4		2	
Household	**Neatwork**	**Field**	**Neatwork**	**Field**	**Neatwork**	**Field**	**Neatwork**	**Field**	**Neatwork**	**Field**	**Neatwork**	**Field**	**Neatwork**	**Field**	**Neatwork**	**Field**	**Neatwork**	**Field**	**Neatwork**	**Field**
Lidia	0.1738	0.0908	0.1745	0.0898	0.1764	0.0905	0.1782	0.0914	0.1820	0.0956	0.1883	0.0995	0.1938	0.1028	0.1966	0.1025	0.1990	0.1055	0.2047	0.1197
Micaela	0.1730	0.1510	0.1733	0.1528	0.1744	0.1518	0.1754	0.1521	0.1775	0.1529	0.1811	0.1566	0.1844	0.1593	0.1866	0.1611	0.1883	0.1632	0.1896	0.1613
Ernesto	0.1778	0.1409	0.1785	0.1378	0.1805	0.1357	0.1823	0.1394	0.1861	0.1396	0.1925	0.1457	0.1980	0.1527	0.2008	0.1572	0.2032	0.1588		
Julia	0.1535	0.1800	0.1552	0.0924	0.1595	0.1048	0.1635	0.1144	0.1717	0.1283	0.1843	0.1461	0.1941	0.1624	0.1978	0.1628	0.2010	0.1644		
Cristina	0.1541	0.1350	0.1546	0.1898	0.1559	0.1882	0.1571	0.1880	0.1597	0.1885	0.1641	0.1954	0.1681	0.1987	0.1706	0.2060				
Minsdu	0.1632	0.0977	0.1649	0.1049	0.1693	0.1077	0.1734	0.1145	0.1818	0.1207	0.1945	0.1353	0.2043	0.1436	0.2077	0.1440				
Rulfina	0.1558	0.1351	0.1562	0.1339	0.1574	0.1319	0.1584	0.1318	0.1607	0.1316	0.1645	0.1322	0.1680	0.1404						
Benita	0.1603	0.1056	0.1616	0.1178	0.1651	0.1182	0.1683	0.1243	0.1751	0.1242	0.1856	0.1438	0.1942	0.1523						
Choli	0.0745	0.0580	0.0824	0.0852	0.1350	0.1569	0.1474	0.1785	0.2044	0.2218	0.2323	0.2534								
Toman	0.0000	0.0404	0.0000	0.0551	0.1318	0.1079	0.1422	0.1186	0.2182	0.1432	0.2436	0.1587								
Abundio	0.0000	0.1424	0.1195	0.2518	0.1304	0.2141	0.2444	0.3288	0.2643	0.3070										
Tito	0.1070	0.0877	0.1531	0.1438	0.1583	0.1368	0.2261	0.2107	0.2390	0.2212										
Alexis	0.1697	0.0305	0.1720	0.0186	0.2243	0.0345	0.2298	0.0398												
Chidtoj	0.1331	0.1728	0.1358	0.1763	0.1733	0.2027	0.1794	0.2195												
Federico	0.1089	0.1118	0.1765	0.2048	0.1800	0.2286														
Virginia	0.0927	0.0790	0.1387	0.1788	0.1444	0.1572														
Martina	0.1663	0.1487	0.1683	0.1453																
Roberto	0.2405	0.2817	0.2415	0.2549																
Anastasio	0.1578	0.1479																		
Augustin	0.1773	0.1706																		

Table 9 shows the difference in each field measured flow compared against the Neatwork estimation flow taken from table 8(field measured flow minus Neatwork estimated flow) and is categorized by the number of taps open in the system for the given measurement and by the household where the faucet was located and flow was measured. A positive number, or gray cell, indicates that the field measured flow was greater than the Neatwork estimated flow, while a negative value, or a white cell, indicates the Neatwork value is greater than the field measured flow (difference = field measured flow- neatwork estimated flow). It can be observed from this table that 79 out of 110 times, the Neatwork simulated flow was greater than the field flow leaving 31 times out of 110 where field flow was greater than simulated flow. Based on this we see that in our comparisons, Neatwork has the tendency to overestimate flows in comparison to what the observed flow is. To understand why this might be, further analysis is carried out.

Table 9. Difference between field measured flow and Neatwork estimated flows. A positive value, or bold cell, indicates a higher field measured flow than Neatwork estimated flow.

	Number of Taps Open									
Household	**20**	**18**	**16**	**14**	**12**	**10**	**8**	**6**	**4**	**2**
Lidia	-0.0830	-0.0847	-0.0859	-0.0868	-0.0864	-0.0888	-0.0910	-0.0941	-0.0935	-0.0850
Micaela	-0.0220	-0.0205	-0.0226	-0.0233	-0.0246	-0.0245	-0.0251	-0.0255	-0.0251	-0.0283
Ernesto	-0.0369	-0.0407	-0.0448	-0.0429	-0.0465	-0.0468	-0.0453	-0.0436	-0.0444	
Julia	0.0265	-0.0628	-0.0547	-0.0491	-0.0434	-0.0382	-0.0317	-0.0350	-0.0366	
Cristina	-0.0191	0.0352	0.0323	0.0309	0.0288	0.0313	0.0306	0.0354		
Minsdu	-0.0655	-0.0600	-0.0616	-0.0589	-0.0611	-0.0592	-0.0607	-0.0637		
Rulfina	-0.0207	-0.0223	-0.0255	-0.0266	-0.0291	-0.0323	-0.0276			
Benita	-0.0547	-0.0438	-0.0469	-0.0440	-0.0509	-0.0418	-0.0419			
Choli	-0.0165	0.0028	0.0219	0.0311	0.0174	0.0211				
Toman	0.0404	0.0551	-0.0239	-0.0236	-0.0750	-0.0849				
Abundio	0.1424	0.1323	0.0837	0.0844	0.0427					
Tito	-0.0193	-0.0093	-0.0215	-0.0154	-0.0178					
Alexis	-0.1392	-0.1534	-0.1898	-0.1900						
Chidtoj	0.0397	0.0405	0.0294	0.0401						
Federico	0.0029	0.0283	0.0486							
Virginia	-0.0137	0.0401	0.0128							
Martina	-0.0176	-0.0230								
Roberto	0.0412	0.0134								
Anastasio	-0.0099									
Augustin	-0.0067									

4.2.1 Flow Trends at Unique Taps Over Varying Number of Open Taps for Neatwork and Field Observations

Another way to understand the trend of flow over various open taps is by using regression plots (Figures 10a,10b, 11a, and 11b). Reviewing these four plots, one can see the overall trend of decreasing flow as number of taps open increases for both Neatwork and field measured flows, as expected, considering that the same flow is being divided up by more taps. As mentioned in the observations of Table 9, it can be seen again that Neatwork tends to overestimate the flows in comparison to the field measured results. Results from certain households that stand out include: Alexis' very low flow output in the field compared to what was expected from Neatwork, the decrease in flow at Roberto's tap, although open faucets decreased from twenty to eighteen, and also, Toman and Abundio never experience zero flow in the field as Neatwork predicts they will for conditions of eighteen and twenty taps open, respectively.

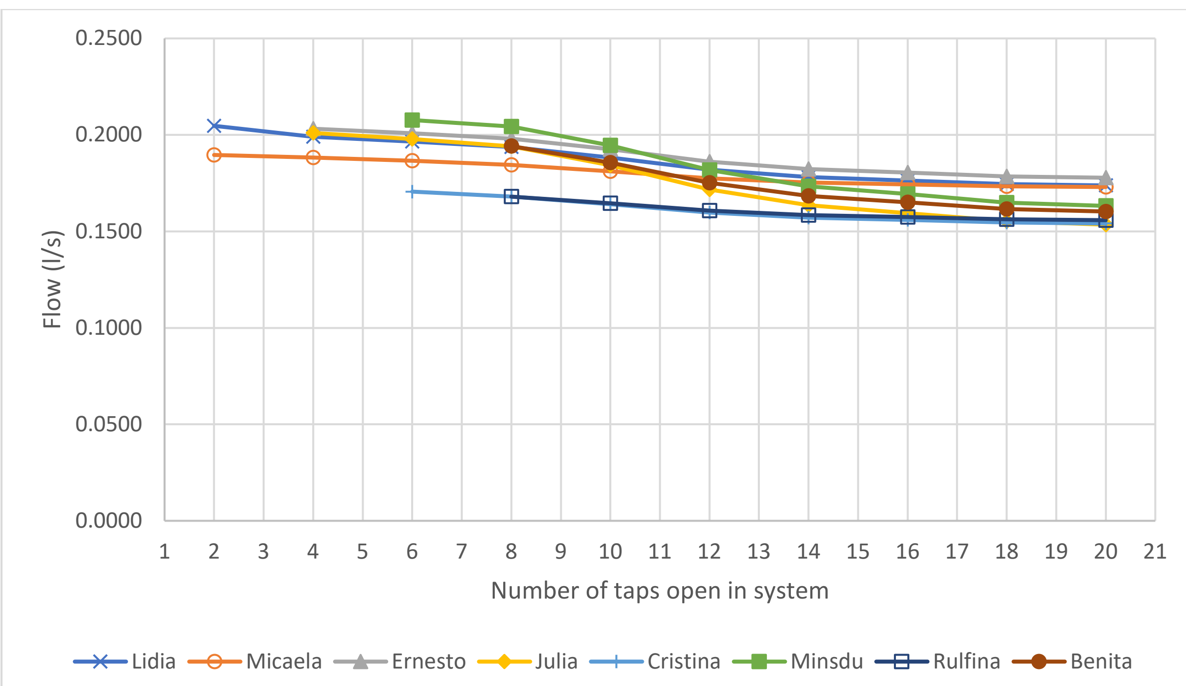

Figure 12a. Plot of number of open taps against Neatwork predicted flow for Lidia, Micaela, Ernesto, Julia, Cristina, Minsdu, Rulfina and Benita's taps.

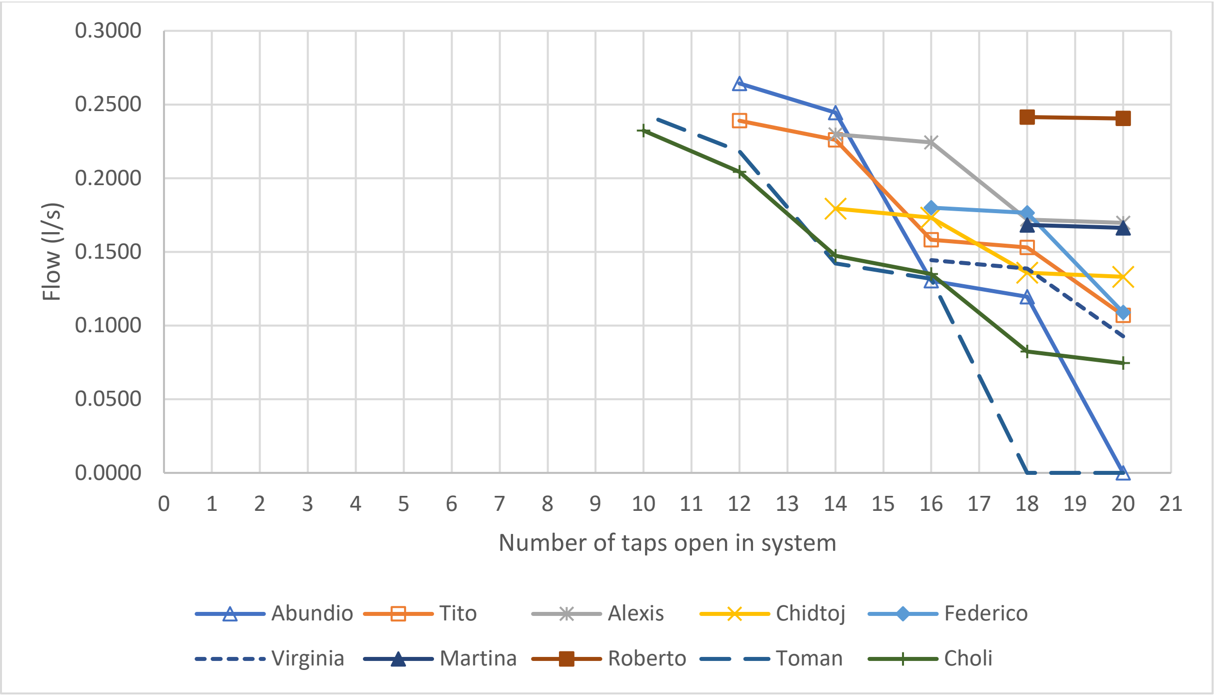

Figure 12b. Plot of number of open taps against Neatwork predicted flow for Abundio, Tito, Alexis, Chidtoj, Federico, Virginia, Martina, Roberto, Toman and Choli's taps.

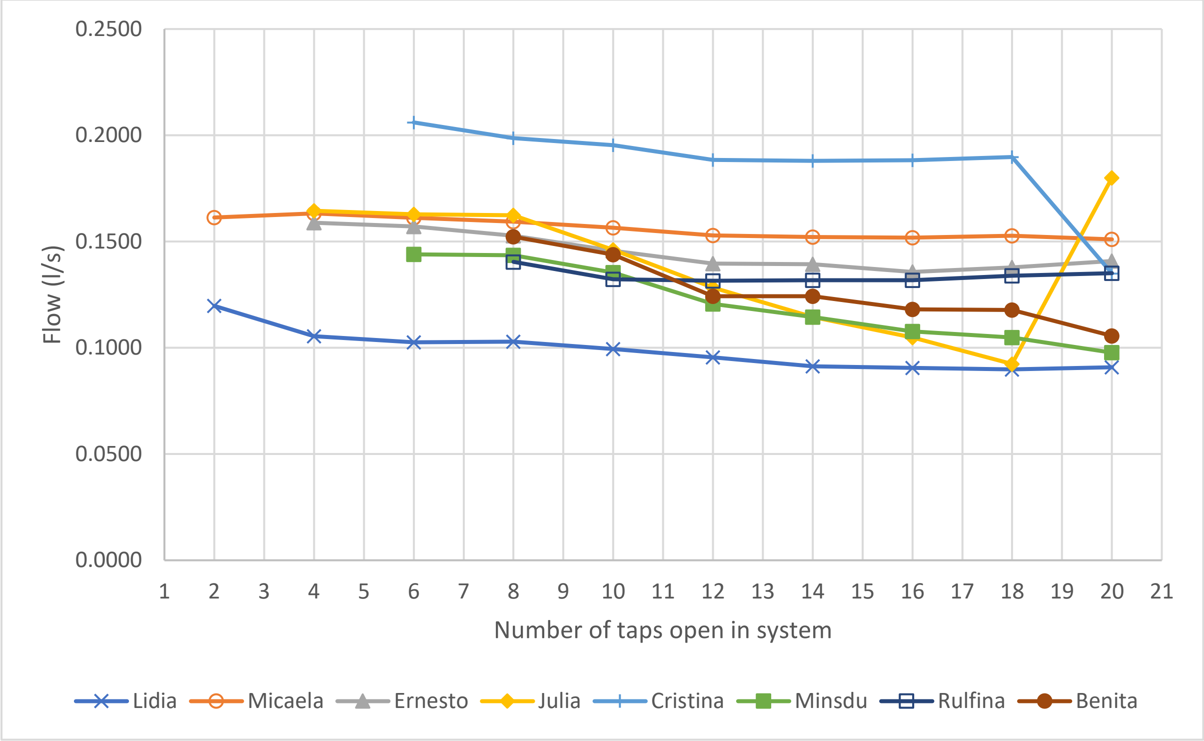

Figure 13a. Plot of number of open taps against field measured flow for Lidia, Micaela, Ernesto, Julia, Cristina, Minsdu, Rulfina and Benita's taps.

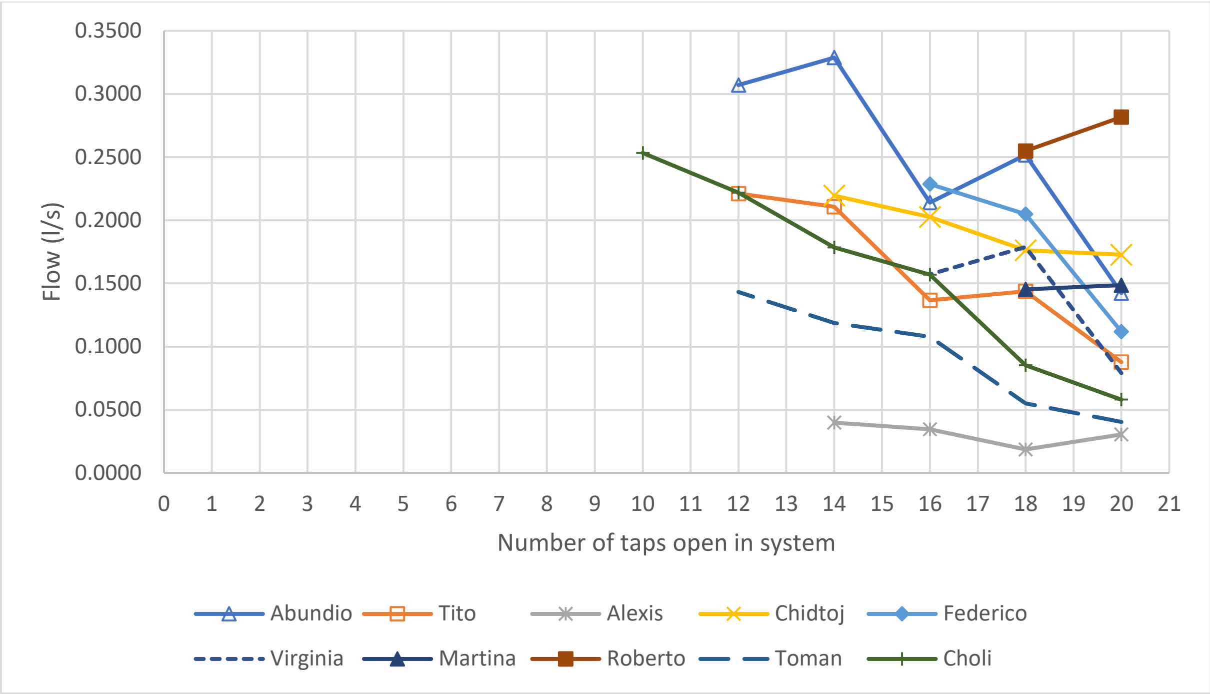

Figure 13b. Plot of number of open taps against Neatwork predicted flow for Abundio, Tito, Alexis, Chidtoj, Federico, Virginia, Martina, Roberto, Toman and Choli's taps.

4.2.2 Variations Between Taps and Number of Faucets Open Using Paired T-Test

4.2.2.1 Suitability of the Paired T-Test

To observe whether a significant change between the field measured flow and Neatwork estimated flow exists, we must develop and test a hypothesis using a statistical test, in our case, the paired t-test.

A paired t-test is a suitable choice for comparing two sets of values where one is interested in determining if the difference in the mean between the two pairs of values is statistically significant. This method is of interest for this research to observe differences in flow for a certain number of open taps over the various households, but also for observing differences in flow at a given household's tap over the various number of open taps. One of the requirements of using a paired t-test, is establishing normality in the population being tested. To aid in determining normality, another statistical test, the Shapiro-Wilks test, will be applied.

4.2.2.2 Results of the Shapiro-Wilks Test

One method of testing whether a sample comes from a normally distributed population is to use the Shapiro- Wilks test. In the Shapiro-Wilks test the null hypothesis (H_o) states that the sample comes from a population which has a normal distribution. One may refer to the original paper on the Shapiro-Wilks method (Shapiro and Wilk, 1965) or other guides that describe the process for using the method and tables associated. Below are the results of the Shapiro-Wilks test for the data presented in Tables 10 and 11 over various number of open and closed taps, and over the measurements per tap/household. A confidence interval of 95% was used (α=0.05) was used for these tests.

Table 10. Results of Shapiro-Wilks test for varying number of taps open.

Taps Open	N	Flow From	Accept Null hyp?
20	20	Simul	No
	20	Field	Yes
18	18	Simul	No
	18	Field	Yes
16	16	Simul	Yes
	16	Field	Yes
14	14	Simul	Yes
	14	Field	Yes
12	12	Simul	Yes
	12	Field	Yes
10	10	Simul	Yes
	10	Field	Yes
8	8	Simul	Yes
	8	Field	Yes
6	6	Simul	Yes
	6	Field	Yes
4	4	Simul	No
	4	Field	No

Table 11. Results of Shapiro-Wilks test by tap location/household.

Household	N	Flow From	Accept Null Hyp?
Lidia	10	Simul	Yes
	10	Field	Yes
Micaela	10	Simul	Yes
	10	Field	Yes
Ernesto	9	Simul	Yes
	9	Field	Yes
Julia	9	Simul	Yes
	9	Field	Yes
Cristina	8	Simul	Yes
	8	Field	No
Minsdu	8	Simul	Yes
	8	Field	Yes
Rulfina	7	Simul	Yes
	7	Field	No
Benita	7	Simul	Yes
	7	Field	Yes
Choli	6	Simul	Yes
	6	Field	Yes
Toman	6	Simul	Yes
	6	Field	Yes
Abundio	5	Simul	Yes
	5	Field	Yes
Tito	5	Simul	Yes
	5	Field	Yes
Alexis	4	Simul	No
	4	Field	No
Chidtoj	4	Simul	No
	4	Field	No
Federico	3	Simul	Yes
	3	Field	Yes
Virginia	3	Simul	Yes
	3	Field	Yes

For varying number of open taps, we do not perform the test for when n=2, as it is too small of as sample size for this test. We can see that for that the case when 20, 18 and 4 taps are open, either the simulated results or both the field and simulated results do not accept the null hypothesis that the sample comes from a normal distribution. For this reason, we will omit the cases of 20, 18 and 4 taps open for statistical analysis where normality is required. It should be noted that accepting the null hypothesis for the other cases only tells us that we do not have sufficient evidence to reject the null hypothesis and it is still possible that normality is inconclusive.

Observing the results of the Shapiro-Wilks test at different taps/households, we reject the null hypothesis for the following households: Cristina, Rulfina, Alexis and Chidtoj. These households will also be omitted from the statistical analysis where normality is a requirement.

4.2.2.3 Results of the Paired T-Test Based on Shapiro-Wilks

Based on the results of the Shapiro-Wilks test, we conduct the paired t-test for the tap. For purposes of this research, a confidence interval of 95% was used (α=0.05) was also applied as it was in the Shapiro-Wilks test. In a paired t-test, the null hypothesis states that there is no significant difference in the mean differences ($\bar{d}$) between the two populations ($\bar{d}=0$) while the alternate hypothesis (H_a) states that there is a significant difference in the mean differences ($\bar{d}\neq 0$) (Shier, 2004).

In order to determine significance, the mean difference of for the aforementioned number of taps open was calculated (16, 14, 12, 10, 8, and 6 taps open) using data from table 8. Next, the standard deviation (s_d) of the differences is calculated and used to calculate the standard error of the mean difference, SE ($\bar{d}$), which is further used to calculate the T statistic, T. Once a T statistic is calculated and the significance level, alpha (α), is established, one can use a T-table to find probability, P. The previously described equations can be found in Appendix C (Shier, 2004).

In the case of calculating mean difference for this research, the absolute value of the means was used. While it is important to note the trend of overwhelmingly and consistently higher or lower differences in flow between field measured flow, which can be observed in Table 9, the objectives of this research are most concerned with whether there are any significant differences at all. Not using the absolute value of the paired differences may reflect overall differences inaccurately in the mean difference. For example, if one house were to experience field and simulated flows of 4 and 6 l/s, respectively, and another house were to experience field and simulated flows of 6 and 4 l/s respectively, an average of these differences would say there is zero difference in flows. This would be appropriate if one were interested in the overall trends in increased or decreased flow. However, for understanding if there is any significant change between the two values and not necessarily their direction, the author has chosen to use absolute values.

A summary of the findings of the paired t-tests for observing the differences in flows over each group of number of open taps is provided in Table 12 and differences in flow over the measurements at each tap/household is shown in Table 13. As previously stated, rejecting the null hypothesis assumes that there is in fact a significant difference between the field measured flow and the Neatwork simulated flow. The P- value represents the likelihood that we accept the null hypothesis, considering our confidence interval of 95%, if the P value is less than 0.05, we can reject the null hypothesis that the samples are not statistically different.

Table 12. T-test results by number of open taps.

Open taps	Sample size, n	T Statistic	P value	Accept H_o?
16	16	4.67	0.0002	No
14	14	4.45	0.0003	No
12	12	6.87	0	No
10	10	6.24	0.0001	No
8	8	5.63	0.0004	No
6	6	4.79	0.0025	No

From Table 12, we observe that for the case of 8 taps open, or 40% taps open, the default condition of Neatwork and objective one of this research, we reject the null hypothesis that the mean difference between field and Neatwork flows are equal. Looking additionally at the other conditions of open/close faucets one can notice that under all other variations of open/closed taps, the null hypothesis is rejected, meaning that there is a significant difference between field and Neatwork produced flow values at 95% confidence level.

Table 13. T-test results by household/location of tap.

Household	Sample size, n	T Statistic	P Value	Accept H_o?
Lidia	10	73.33	0	No
Micaela	10	35.28	0	No
Ernesto	9	42.00	0	No
Julia	9	10.80	0	No
Minsdu	8	76.57	0	No
Benita	7	25.14	0	No
Choli	6	4.89	0.0023	No
Toman	6	4.78	0.0025	No

Observing Table 13, which shows T-test outcomes by the household where each tap resides, we can see similar outcomes. The null hypothesis is rejected meaning that there is no mean difference between Neatwork flow values and field measured flow values for all taps tested using the paired t-test (Lidia, Micaela, Ernesto, Julia, Minsdu, Benita, Choli and Toman). As previously mentioned the t- test was not applied to houses that failed the Shapiro-Wilks test for normality or where $n < 6$.

There are several reasons why many of the results from the T-test demonstrate a lack of similarity in mean difference. It is important to remember that while a low P value demonstrates that it is unlikely one will accept the null hypothesis, it does not explain whether this is due to a true difference in the data or that the sample used was unusual. In the case that the data is unusual one might consider the quality of the flow disk installed at each house. While each flow disk was constructed in the traditional way that a Peace Corps volunteer with limited access to electricity would make them, this likely led to significant variations in flow results from what was expected. One way to observe this would be to calculate the standard deviation of differences in neatwork versus field flows at each tap location. If the model were a perfect representation of what was measured in the field, the differences in flow and thus their standard deviation should be zero. Also, because the taps had the same flow disk for all measurements, even a poorly made flow disk should yield a low standard deviation in flows for that particular tap. Noticing a trend over each tap's results, versus a trend over varying combinations of open/closed taps, would further confirm the notion that at least one of the sources of error, is a tap household dependent variable, in other words, the error is a result of the tap and not the combination of taps opened. Standard deviation was calculated over the flow differences (neatwork versus field) for each tap, as well as over the results for the different combinations of number of open and closed taps.

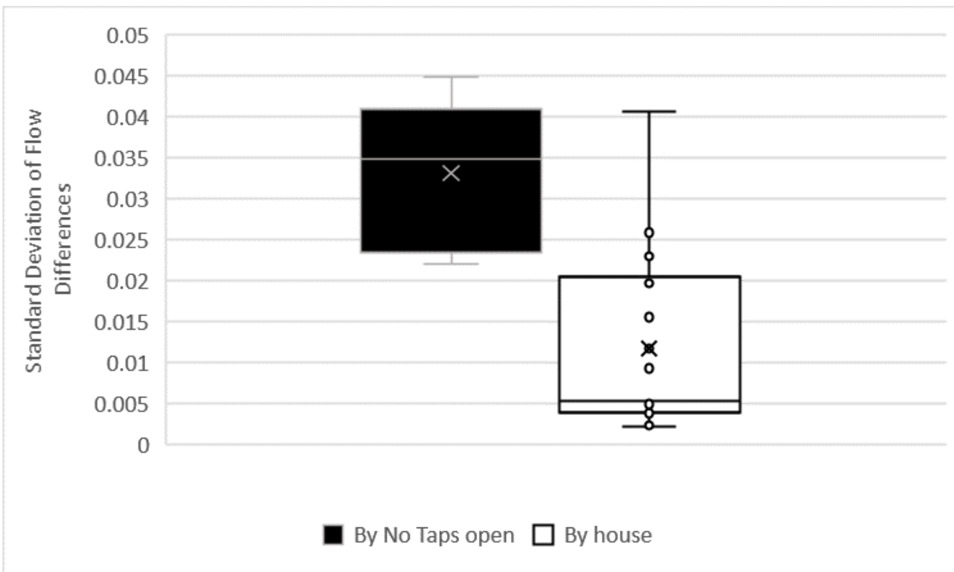

Figure 14. Box plot of standard deviations for differences between field measured flow and Neatwork simulated flow by varying number of open taps (left) and by varying tap house locations (right).

Comparing the box plots in Figure 14 it can be observed that the average standard deviation when comparing flow results over combinations of open/closed taps is much larger than comparing standard deviation over the individual taps. This supports the idea that it is more likely a tap household dependent, rather than combination of open taps dependent, factor affecting the mean differences between field measured and Neatwork simulated flow. The table of exact values used to make Figure 14 can be found in Appendix C.

This idea can also be visually observed in Table 9 where field flows that are greater than simulated flow are displayed in grey cells and simulated flows that are greater than field flows are displayed in white cells. The sign which the differences occur also have the tendency to be consistent over the tap household as opposed to the number of taps being open.

Concluding that the sign and magnitude of flow difference is likely a result of one type of tap household dependent variable, this further supports the assumption that the flow disks and their quality yielded a poor outcome for flow comparison between Neatwork estimated and field measured results.

Aside from inaccurate flow disk production, another reason for variation between taps could be an inaccuracy in topography measurements. As previously mentioned, topography was measured in the field using a clear tubing fixed on either end of rigid poles, marked in inches. Moving downstream of the proposed water distribution, the change in the water level in the tubing was recorded, easily read off the marked PVC it was adhered to. Moving from the highest elevation, all the way down to the location of the where the last tap would be located, the poles would move incrementally reaching the furthest house. If one house were to have been more accurately measured than another, this error would be uniform across all the measurements for that one particular household, as the same topographic measurements were used for all flow measurements and neatwork simulations. That is not the case for the error across all houses for a given combination of open faucets. This could be true for homes that are particularly close together in distance and elevation, such as the cluster of 8 houses (Lidia, Cristina, Micaela, Julia, Minsdu, Rulfina, Ernesto, Benita) (See Figure 15).

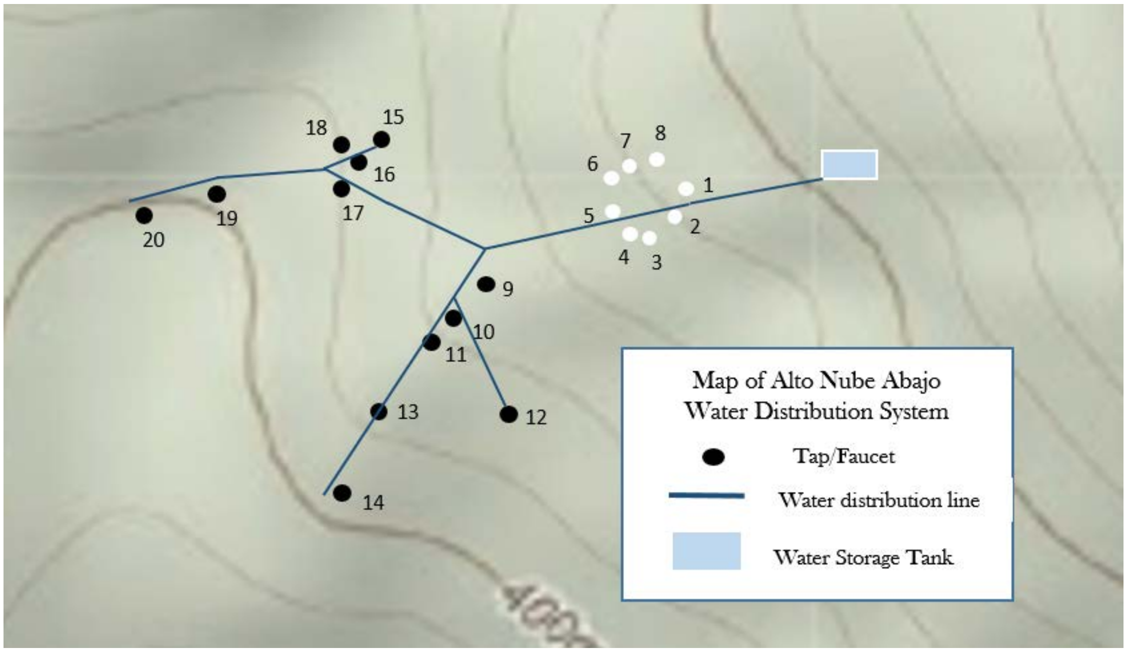

Figure 15. Location of closely clustered homes; Lidia, Cristina, Micaela, Julia, Minsdu, Rulfina, Ernesto, Benita (white circles).

4.2.3 Distance from Water Storage

One similarity between the houses that accept the null hypothesis ($\overline{d}=0$) is their overall distance from the water storage tank. It was previously mentioned that smaller sample sizes have the tendency to result in acceptance of the null hypothesis than larger sample size does on the paired t-test when the sample is not very normally distributed. Coincidentally, the houses furthest away from the tank are the houses with smaller sample sizes. In order to verify whether distance from the water storage tank had an effect on the accuracy of flow, or if what is being observed is just a small enough sample size to accept the null hypothesis, it would be necessary to mix the sample sizes over the length of the system.

Contrary to the previously mentioned results, it would be logical that the flows at the houses furthest from the tank are the measurements to be least accurate from a human error perspective. Generally, the houses furthest from the water storage tank, like in this system, have the smallest flow orifice sizes. The smaller the hole needed and the less accurate the method for making the hole, the more likely there is for the effects of the poorly created hole to be substantial on flow. These houses further and at a greater elevation change away from the tank also have the highest flow rate and pressure, making it more difficult to measure flow in the field as detailed in the methods section (see Chapter 3). This makes it difficult to explain why the three smallest differences between Neatwork flow and field measured flow are for Federico, Anastasio and Augustin (0.0029, 0.0099, 0.0067 L/s respectively) considering they are some of the furthest houses from the storage tank. Figure 13 below depicts the location of these houses with respect to the water source and rest of the distribution system more clearly.

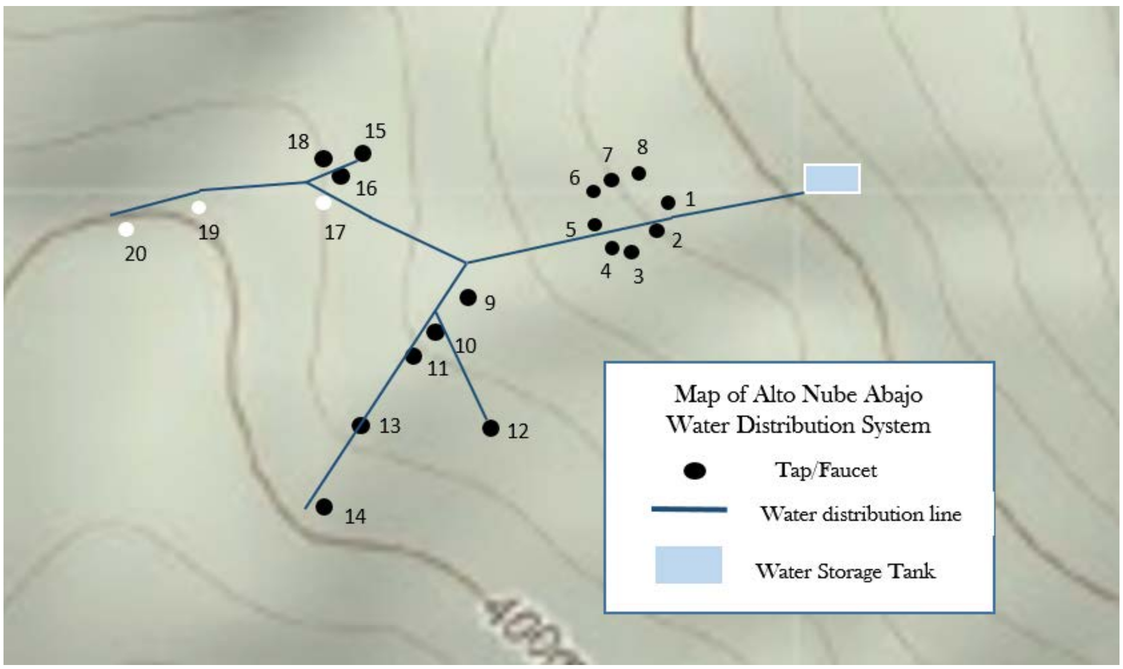

Figure 16. Location of taps with smallest difference between field and Neatwork simulated flow; Augustin, Anastasio, and Federico (white circles).

4.3 Condition 2: Water Level at Tank Outlet vs. Water Level at Tank Overflow

Condition two was carried out to understand the effect of assuming that the elevation of water in a tank is negligible. That is, condition 2 was set to address whether the height of water in the tank of a system contributes to a change in flow. Neatwork uses the conservative scenario as default, where the elevation of the tank to be used is not the height of the water in the tank, but rather, the height of the outlet which is at the bottom of the tank. As a reminder, only Lidia and Micaela's flow measurements were observed for this comparison, due to the incompatibility with orifice disks for the other taps in the field, as described in Table 7.

4.3.1 Neatwork Vs Measured Flows: Water Level at Tank Overflow

As can be seen in Figure 17, for the condition where the water elevation is set to the tank overflow, there is a substantial difference between the measured flow and neatwork flow, with the neatwork predicted flow being 83% greater than the measured flow. Though there is much less of a difference found between the measured and neatwork predicted flows for Micaela's tap (Figure 18), as the neatwork flow is only 27% larger than the field measured flow. In section 4.2 the idea was proposed that resulting errors were likely to be caused by tap dependent variables, such as poorly made flow disks or poor surveying. This idea is reiterated in this data because such a larger difference at Lidia's tap is observed compared to Micaela's tap.

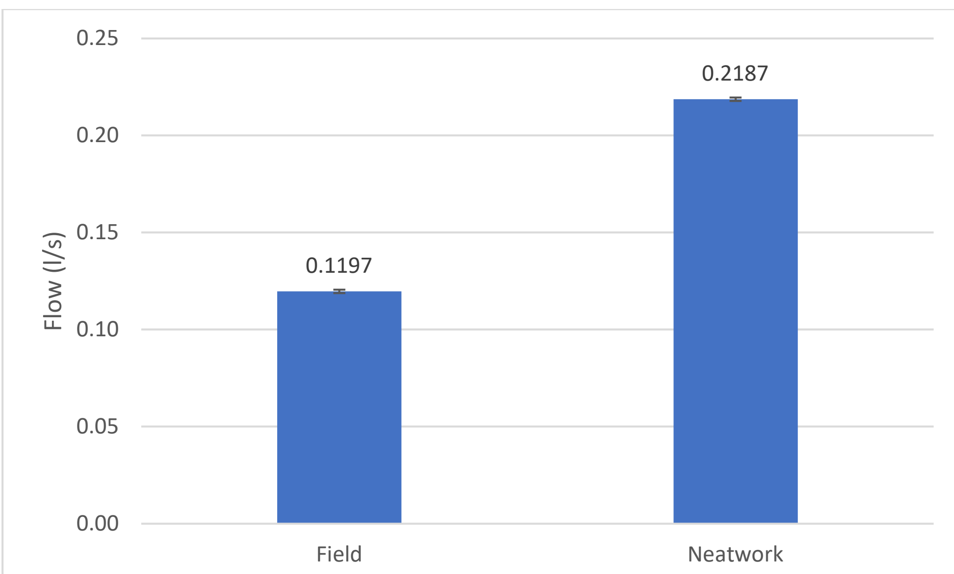

Figure 17. Comparison of measured and neatwork flow at 10% faucets open at Lidia's tap where water elevation is at the tank overflow. Standard error from field measurements is 0.00089 l/s.

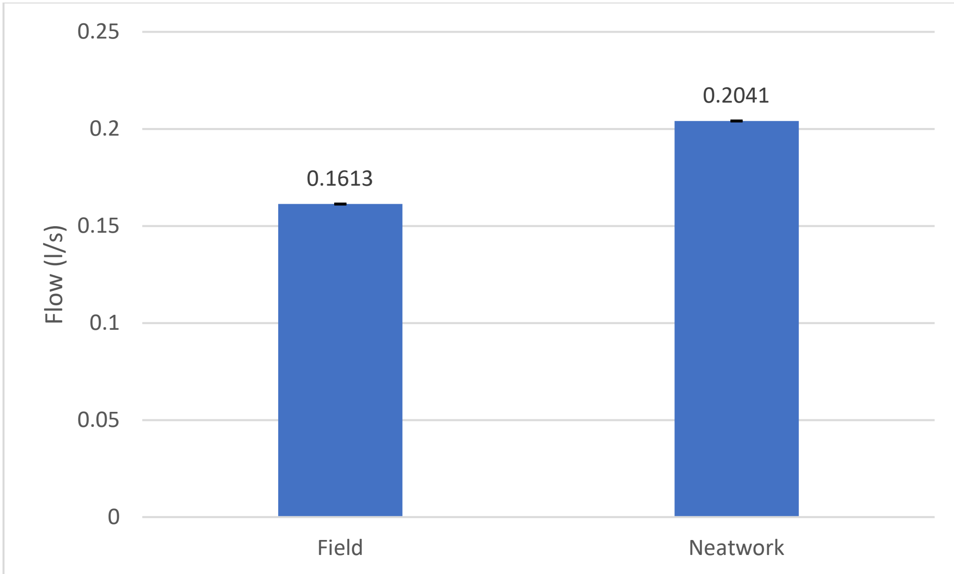

Figure 18. Comparison of measured and neatwork flow at 10% faucets open at Micaela's tap where water elevation is at the tank overflow. Standard error from field measurements is 6.87E-05 l/s.

4.3.2 Neatwork vs. Measured Flows: Water Level at Tank Outlet

For the condition where the water level is at the tank outlet (Figure 19), there is yet again a large difference between the measured flow and predicted neatwork flow for the tap at Lidia's house, with neatwork predicting a flow that is 71% greater than the measured flow. Micaela's tap has a much closer measured flow to neatwork flow, with Neatwork flow being 17% greater than the measured flow (Figure 20).

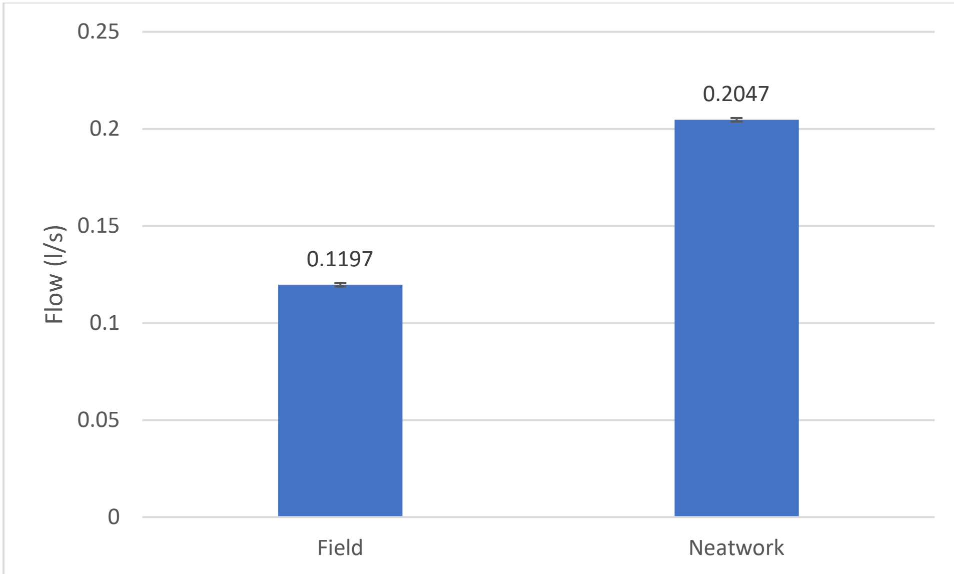

Figure 19. Comparison of measured and neatwork flow at 10% faucets open at Lidia's tap where water elevation is at the tank outlet. Standard error from field measurements is 0.00089 l/s.

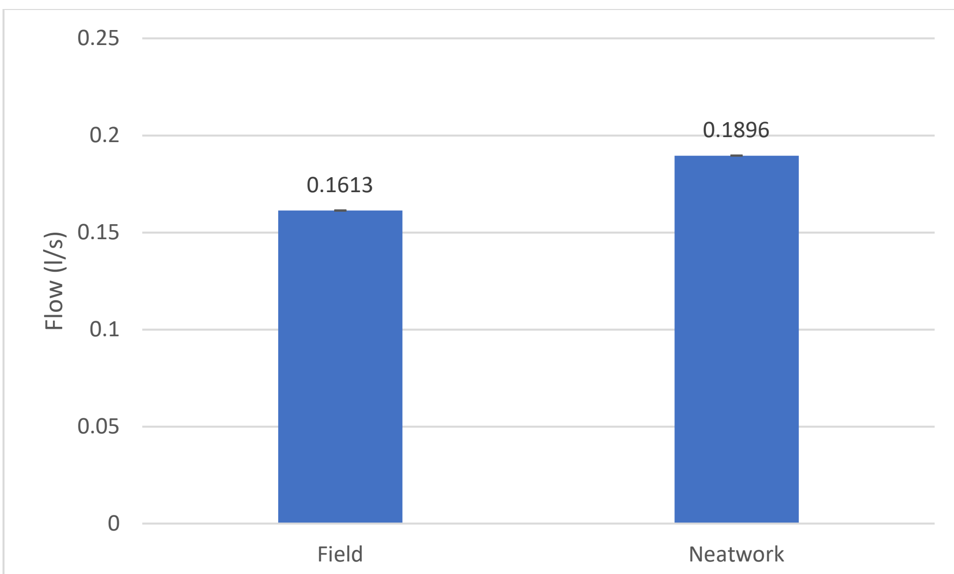

Figure 20. Comparison of measured and neatwork flow at 10% faucets open at Micaela's tap where water elevation is at the tank outlet. Standard error from field measurements is 6.87E-05 l/s.

Overall, we see that changing the elevation from the tank outlet (at the bottom of the tank) to the tank overflow where a full tanks water elevation would be (at the top of the tank), increased flow at Micaela and Lydia's taps by 0.014 and 0.0145 l/s respectively.

4.3.3 Water Level at Tank Outlet Vs. Water Level at Tank Overflow

Comparing the neatwork flows for Lidia and Micaela with the water elevation being at the tank outlet versus the tank overflow, the expected trend can be seen, where the water elevation at the tank overflow yields higher flow under both conditions. This is expected because as head increases by any amount, without a change in distance, we expect to see an increase in flow. For the case of the Neatwork produced results at Lidia's tap, the flow where the water elevation is at the tank outlet is 0.2047 l/s while the flow at the same tap for water elevation at tank overflow is 0.2187 l/s, an increase of 0.0140 l/s. In the case of Micaela's tap Neatwork predicts a flow of 0.1896 l/s for water elevation at tank outlet and 0.2041 l/s for water elevation at tank overflow, a difference of 0.0145 l/s. The difference in flow between the two taps for the two conditions are nearly equal, as could be anticipated for two taps so close together in elevation and distance (Micaela and Lidia are houses 2 and 3 respectively in Figures 7, 15 and 16). While a 0.0140 to 0.0145 l/s increase in flow may not appear to be substantial, it can be the difference between being within a designer's allowable range of flow for all taps or not. It should be noted that this is not the case in this system, as the change in flow still maintains the faucets within the 0.1-0.3 l/s range that is recommended by Neatwork. A small increase in flow as seen in this case may not be substantial enough to merit changing the Neatwork premise of where the water level of the tank lies, since under its current assumptions, it allows for an added factor of safety in flow estimation where other inaccuracies in the system may overestimate flow. While the flow difference may not likely be substantial enough to change whether the tap's flow is within desired range, it is enough of an increase to see a change in the size of flow disks in a system as seen in this case.

4.4 Condition 3 and Condition 4: Orifice Coefficient θ= 0.62 and Orifice Coefficient θ= 0.68

In Drake's study (Drake, 2015) she compares the accuracy of field data collected to Neatwork flow data for various orifice coefficients. She found that an orifice coefficient of 0.68 created the most closely correlated relationship. On the other hand, the Neatwork manual recommends a default of 0.59 while communications that both Drake (Drake, 2015) and the author had (February, 2017) with one of the Neatwork developers suggests 0.62 for the value of orifice coefficient. Considering these various recommendations for orifice coefficient, the author compared 10 to 40% faucets open for an orifice coefficient of 0.62 and 0.68. The author chose to compare for this range of faucets open as the combinations allowed for orifice sizes at all the houses included to match in the field and within Neatwork. The results of field measured and Neatwork estimated flow for this condition with orifice coefficient of 0.62 can be seen in Table 16 and for an orifice coefficient of 0.68 can be seen in Table 17.

Table 14. Neatwork and field produced flows for θ=0.62.

	Taps Open							
Household	8		6		4		2	
	Neatwork	Field	Neatwork	Field	Neatwork	Field	Neatwork	Field
Lidia	0.1492	0.1028	0.1512	0.1025	0.1527	0.1055	0.1783	0.1197
Micaela	0.1726	0.1593	0.1743	0.1611	0.1757	0.1632	0.1765	0.1613
Ernesto	0.1526	0.1527	0.1545	0.1572	0.1561	0.1588		
Julia	0.1833	0.1624	0.1857	0.1628	0.1877	0.1644		
Cristina	0.1565	0.1987	0.1586	0.2060				
Minsdu	0.1929	0.1436	0.1952	0.1440				
Rulfina	0.1577	0.1404						
Benita	0.1830	0.1523						

Table 15. Neatwork and field produced flows for θ=0.68.

	Taps Open							
	8		6		4		2	
Household	Neatwork	Field	Neatwork	Field	Neatwork	Field	Neatwork	Field
Lidia	0.1580	0.1028	0.1595	0.1025	0.1608	0.1055	0.1639	0.1197
Micaela	0.1501	0.1593	0.1513	0.1611	0.1523	0.1632	0.1530	0.1613
Ernesto	0.1605	0.1527	0.1620	0.1572	0.1634	0.1588		
Julia	0.1584	0.1624	0.1604	0.1628	0.1622	0.1644		
Cristina	0.1349	0.1987	0.1363	0.2060				
Minsdu	0.1670	0.1436	0.1689	0.1440				
Rulfina	0.1379	0.1404						
Benita	0.1583	0.1523						

In order to understand which orifice coefficient yields a flow closer to the field measured flow, a simple calculation for the absolute value of differences for every neatwork and field measured flow was carried out, both for orifice coefficient of 0.62 and 0.68 (Table 18 and 19, respectively).

Table 16. Absolute value of differences between Neatwork and simulated flow for orifice coefficient of 0.62.

	Taps Open			
Household	**8**	**6**	**4**	**2**
Lidia	0.0464	0.0484	0.0487	0.0502
Micaela	0.0133	0.0150	0.0132	0.0146
Ernesto	0.0001	0.0018	0.0027	
Julia	0.0209	0.0233	0.0229	
Cristina	0.0422	0.0401		
Minsdu	0.0493	0.0516		
Rulfina	0.0173			
Benita	0.0307			

Table 17. Absolute value of differences between Neatwork and simulated flow for orifice coefficient of 0.68.

	Taps Open			
Household	**8**	**6**	**4**	**2**
Lidia	0.0552	0.0567	0.0570	0.0583
Micaela	0.0092	0.0080	0.0098	0.0088
Ernesto	0.0078	0.0093	0.0048	
Julia	0.0040	0.0020	0.0024	
Cristina	0.0638	0.0624		
Minsdu	0.0234	0.0253		
Rulfina	0.0025			
Benita	0.0060			

A summary of which orifice coefficient (0.62 or 0.68) yielded a closer result to the field data can be seen below (Table 20). In the table cells labeled "0.62" signify that the Neatwork results using an orifice coefficient of 0.62 resulted in a closer relationship to the field value than the orifice coefficient of 0.68 cells labeled "0.68" signify a closer comparison for Neatwork results produced with an orifice coefficient of 0.68.

Table 18. Summary of which orifice coefficient (0.62 or 0.68) used in Neatwork resulted in closer flow results to the field data.

	Taps Open			
Household	**8**	**6**	**4**	**2**
Lidia	0.62	0.62	0.62	0.62
Micaela	0.68	0.68	0.68	0.68
Ernesto	0.62	0.62	0.62	
Julia	0.68	0.68	0.68	
Cristina	0.62	0.62		
Minsdu	0.68	0.68		
Rulfina	0.68			
Benita	0.68			

From these results we see that 11 out of 20 times the orifice coefficient of 0.68 was a closer match to the field measured flow than the orifice coefficient of 0.62, while 9 out of 20 times the orifice of coefficient of 0.62 was closer to the field measured flow than 0.68. As can be seen, the number of times that one orifice coefficient was closer to the field measured values over another is nearly equal.

One other pattern that can be seen in this case is the tendency for one orifice coefficient to be closer to the field measured flows for all measurements over one faucet. For example, Lidia's field flow measurements are always closer to the Neatwork flow measurements when the orifice coefficient used is 0.62. This can also be seen at Micaela's tap, where her field flows are more like flows simulated in Neatwork using an orifice coefficient of 0.68. From this it can be concluded that, in this case of field measurements, the orifice coefficient that is most fitting changes with the tap location.

While the results of this comparison do not yield conclusive results as to which orifice coefficient (0.62 or 0.68) will produce results closest to our field measured values, it does support the idea that the field produced results are with error. This error is likely to derive from a variable that is dependent on each independent faucet.

4.5 Acceptable Confidence Interval

In order to address the objectives of this research, it is important to define what "significant difference" can be considered when comparing modeled and field measured flow results. For engineering and statistical purposes, the threshold for significant difference is widely accepted and measured by a confidence interval of 95%. This is not as easily agreed upon in the context of a community's acceptance of difference in flow between field and simulated flow. Whether a water system user accepts or does not accept the difference between the flow in Neatwork or another simulation program and the flow they experience at a given tap in person is dependent on the expectations of each user. In the case of this research a user at Alexis' tap, who takes seventeen minutes to fill one five-gallon bucket may not find the comparison between the program and what is actually experienced to be significantly similar. On the other hand, someone at Micaela's tap, may not find a mean difference of flow of 0.0241 l/s to be significantly different for their practical purposes. Although these cases to each user may not appear comparable, the results from the paired t-test give the same results: the mean difference between Neatwork flow and field flow is significantly different. While the comparison using a paired t-test is a well-established and defined method for determining differences between two sets of paired data, it may not be flexible enough to include the community member's perception of "significant difference".

4.6 Effect of Field Measurement Method on Results Accuracy

While it is impossible to know with certainty the ways that field data may have been inaccurately measured, the author believes that there are steps that could be taken to control the field condition and the measurements better for future work related to this research. Some of these steps would perhaps increase the difficulty of coordinating the measurements and these should be considered, as these measurements affect the community's use of water and therefore their daily routine. Some may be impossible due to the nature of the Neatwork program and how unlikely it is to take into consideration a field measurement flaw but are still worth discussing.

One example of this is measuring the orifice of each flow disk fabricated instead of averaging the orifices produce by a nail of unique diameter. This would allow the user to input the known orifice size for each individual flow disk created, considering that each unique nail size will not produce perfectly consistent results with the method used in this work (see Chapter 3. Methods). While this is ideal, it is nearly impossible to execute as the Neatwork program will assign flow disks to each tap based on the available sizes the user inputs. If the user inputs, for example, twenty unique orifice sizes measured individually to account for discrepancies in hole making, Neatwork may choose only a handful of these sizes, as opposed to all twenty. If this were the case, the user would be forced to install two or more of the exact same orifice sizes at multiple taps which, as established, is nearly impossible to fabricate due to the method used in this research.

Another challenge of this field work is not impossible but laborious in the field and relates to changing the design parameters to simulate different conditions in Neatwork. Every time a design aspect changes in Neatwork, such as changes to topography or design parameters such as orifice coefficient, Neatwork has the opportunity to change the assignment of the flow disks. This means if one were to compare, for example, ten different orifice coefficients, in Neatwork to field measurements, resulting in ten different design, it is possible that the user may need to install any or all of the flow disks in the whole system, up to ten times. In the field this requires, physically unburying the part of each household tap's personal water line where the old flow disk is removed and the new one to be installed. This is time consuming, labor intensive and requires water to temporarily be cut off to that individual tap for the duration of the work being done on it. The portion of pipe could be left unburied for the duration of measurements to more easily change the flow disk, but this is not recommended, as exposed PVC pipe can easily be damaged and a trench in a high foot traffic location could pose a risk. As mentioned, while this is not impossible, it would be challenging.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

Peace Corps volunteers in Panama and other development workers in rural areas use the Neatwork program to aid in the design and development of water distribution systems in a rural context. The neatwork program, which is developed upon essential hydraulic principles that predict the flow of piped gravity fed water distribution systems, should be validated against an existing system to confirm the accuracy of the model. To address the following objectives of this research the objectives were: (1) to compare the flow measured at faucets in a rural gravity fed water distribution with estimated flow results produced in the program Neatwork under default conditions to determine if the program produces accurate results (2) If the flows are found not to be comparable, use variations in the percent of open faucets to determine the effect that the percent of faucets open in a community has on the accuracy of Neatwork. (3) Verify that the flow at the designated faucet falls between the estimated flows from Neatwork for two scenarios: water tank height at the tank outlet and water tank height at the overflow.

5.1 Conclusions from Objective 1

To address objective 1 a paired T-test was performed to determine if there was a mean difference between Neatwork and field results for the case of 40% taps open in the system, the default condition for Neatwork simulations. From Table 12 in Chapter 4, it can be seen that for the default case of 40% taps open, or in this system, eight taps open, the null hypothesis was rejected and we do not accept that the mean difference between field flow and Neatwork simulated flow are the same. Observing Table 9 we note that for the case of eight taps open, Neatwork overestimates flow compared to the field results. An overestimation of flow in the Neatwork program is likely more of a concern for water system users in comparison to an underestimation, as users will anticipate and plan their use according to this greater flow, only for it to fall short of expectations. For a further understanding of this result, objective two must be addressed.

5.2 Conclusions from Objective 2

Based on the results of the paired t-test which compared the mean differences over the conditions of varying number of taps open (30-80% taps open, or 6-16 individual taps open after determining normality based on the Shapiro-Wilks test) one concludes that the results were not comparable between any combination of taps open. Comparing figures 12a and 12b with 13a and 13b, as concluded from objective 1, one can observe that the Neatwork model continues to overestimate flow over various conditions of open and closed faucets, a potentially impactful consequence for users. While the tests applied determined that the two samples are statistically different, the author believe that there is an important effect on field flow due to unusual data that was collected, which the paired t-test alone could not reflect. To further investigate the possibility that the samples are unusual, the author compares differences of neatwork and field flow over individual taps versus over varying number of taps open and finds that the standard deviation tends to be much lower over individual taps. This demonstrates that a variable affecting the difference in neatwork and field flow is likely related to a factor dependent on each unique tap, such as the flow disk at this tap or the surveying associated with it. Observing the trends of positive and negative differences in field and Neatwork flow (Table 9) reinforces this, as they are typically consistent with the tap location.

Despite using the Shapiro-Wilks test to determine normality, a lack of similarity in mean differences could still be due to abnormalities in the distribution of the flow results, where there is simply not enough evidence to deny the fact that the samples are not normally distributed.

5.3 Conclusions from Objective 3

In the comparison of flows at Lidia and Micaela's taps under the two conditions where the water elevation in the tank is at the tank overflow (top of tank) versus the tank outlet (bottom of tank) we do see that the flow still falls within the desired range with the former Neatwork flows at Lidia and Micaela's taps being 0.2047 and 0.1896 l/s respectively and the new flow where water level is at tank outlet being 0.2187 and 0.2041 l/s respectively. In the case of this water system and the combination of these two taps being open, this does not change whether the flow rates fall within the desired range of 0.1 to 0.3 l/s, which is a reasonable range determined by Neatwork. This could be the case for another system or another combination of open faucets, but it is not recommendable to assume the water elevation of the tank to be at the overflow. Assuming the level of water in the tank is conservative and serves as a factor of safety in design which may compensate for imperfections in construction, varying levels of water height in the tank due to low flow from the water source or high demand in the community and other unforeseen circumstances that reduce the efficiency of the system.

5.4 Other Conclusions from this Research

One of the observations made in this research which was not originally an objective, relates to the comparability of field and Neatwork flows when analyzing results by household. One pattern that was observed was the closeness in flow difference between field flows and Neatwork flows at each household. This was measured by calculating standard deviation at each household's tap for the differences in-field and Neatwork flow over all the relevant combinations of open taps. This showed that at a given tap, no matter which combination of taps were open in the system, the difference between the field and Neatwork flow was about the same. From this we could attribute the disparity between field and Neatwork flow to a variable dependent on the individual taps, such as poorly made flow reducers or inaccurate surveying.

Also tested were the closeness of field results to Neatwork results when two different orifice coefficients, different from the Neatwork manual recommended value, were applied. From this, such inconsistent results were produced that the only conclusion that could be drawn was that the orifice coefficient that matched most closely with the field flow, was dependent on the faucet. This further reinforces that the dominating variable to affect the closeness of field flow results to Neatwork simulated results, was tap dependent, such as in the case of inaccurately sized flow reducers or poorly done surveying.

5.5 Recommendations for Future Research

While this work does not verifiably determine whether the Neatwork model itself produces accurate flow results when measured against flow in an existing water distribution system, this research does call attention to the reality of the conditions in which these systems are made, and how that affects the comparability of a precisely defined program such as Neatwork. This is not to say that such a computer program is not worth using, nor does it demand that rural gravity fed water systems meet the construction/development requirements that a program such as Neatwork is built upon. A program such as Neatwork informs a designer on what design conditions they may want to consider when they are developing the framework for a water system, while also giving the user control to prioritize different aspects of the system, such as cost-efficiency over service quality or vice-versa. This research does, on the other hand, shed light on the reality that many communities utilizing flow reducers in their systems will not have the means to create accurate orifice sizes that will allow them to predict what kind of flow will be produced at a faucet.

To establish with more certainty the accuracy of Neatwork with real-world applications of rural water distribution systems, a method for creating and measuring orifices in flow reducers should be established and tested. Another common method to create these orifices, as Roy (2017) details, is using drill bits of varying diameters. This alone may not be an accurate enough method, though, and others should be investigated. It would be most beneficial to this field of work, if this new method of creating flow reducers could be established and adapted for communities with limited resources. Perhaps, if made on a large scale by one fabricator and distributed for an affordable price, this could result in an economical and improved way of incorporating flow reducers into rural water distribution systems.

The author also recommends that in order to more accurately verify the Neatwork model against an actual rural gravity fed water system, the field measurements carried out in this research should be carried out again over a larger sample size of houses and with a more randomized combination of open/closed faucets. This is especially necessary to understand whether the acceptance of the null hypothesis for objective two, where the null hypothesis means there is no statistical difference between the means of field flows and Neatwork simulated flows, is true or is a result of normality or lack thereof. It should be noted that field measurements of this sort can be difficult to execute in a community where the water distribution is depended upon daily and involves much coordination, participation and flexibility with the community. The impacts that this type of research can have on the participating community should be thoroughly understood and communicated with all parties affected and involved.

To get a full understanding of the role that each input variable plays in the accuracy of the Neatwork model, a full sensitivity analysis should be carried out. This would include raising and lowering each input variable that affects flow in the neatwork program by incremental amounts, to see which of these inputs are more sensitive to change than others. An understanding of which variables are most sensitive to change would guide the user in understanding which values may change the output of the simulation most when adjusting.

The tools and methods used to enhance performance, including equity, of a water system should produce results that are suited to the expected results of the system, in this case, sufficient flow. This applies to the computer programs that are used to design and analyze these systems, like Neatwork, as well as the methods for installing and fabricating control devices such as flow disks. This should be taken into consideration when improving upon the sustainability of flow disks in a rural context; an accuracy as large that was reflected in Alexis' house is clearly not acceptable, but 95% percent confidence that two values are similar may also be unnecessary. It is important that designers, community members and researchers come together to have this conversation in order for sustainability to be achieved.

REFERENCES

Agua Para La Vida. "Home". Agua Para La Vida, 2014. Web. 19. Sep. 2017.

Agua Para La Vida. "NeatWork: A User Guide". Agua Para La Vida, 2010. Web. 3. Nov. 2014.

Drake, Briana I., Improving Flow Distribution in Small-Scale Water-Supply Systems through the Use of Flow-Reducing Discs and Methods for Analyzing the Effectiveness of Solar Powered Pumping for a Drinking Water Supply in Rural Panama. Thesis. Michigan Technological University, 2015. https://www.mtu.edu/peacecorps/programs/civil/pdfs/briana-drake-thesis-final.pdf.

Green, Kaitlin Elinor, *Embodied Energy Assessment of Rainwater Harvesting Systems in Primary School Settings on La Peninsula Valiente, Comarca Ngöbe Bugle, Republic of Panama*. Thesis. University of South Florida, 2011. https://usfmi.weebly.com/uploads/5/3/9/2/5392099/final_thesis_green_kaitlin.pdf

Houghtalen, Robert J., et al. *Fundamentals of Hydraulic Engineering Systems*. 4th ed., Pearson, 2010.

Jordan, Thomas D. *A Handbook of Gravity-Flow Water Systems for Small Communities*. Practical Action Publishing, 1984.

Manser, N., Naughton, C., Prouty, C., Orner, K., Verbyla, M., & Mihelcic, J.R. "Improving the Global Competency of Graduate Engineers Through Peace Corps Partnership and Long-Term International Service. Making Value for Society". Proceedings of the American Society for Engineering Education (ASEE) National Conference, Washington Convention Center, Seattle, WA, June 2015.

Mihelcic, J.R. "The Right Thing to Do: Graduate Education and Research in a Global and Human Context," in What Is Global Engineering Education For? The Making of International and Global Engineering Educators (Eds: G.L. Downey and K. Beddoes), Morgan & Claypool Publishers, San Francisco, pg 235-250, 2010.

Mihelcic, J.R., Myre E.A., Fry L.M., Phillips L.D., Barkdoll, B.D. *Field Guide in Environmental Engineering for Development Workers: Water, Sanitation, Indoor Air*. American Society of Civil Engineers. (ASCE) Press, Reston, VA, 2009

Mihelcic, J.R., Phillips, L.D., Watkins, D.W. ”Integrating a Global Perspective into Engineering Education & Research: Engineering International Sustainable Development,” Environmental Engineering Science, 23(3):426-438, 2006.

Modeling of Chlorine Decay in Drinking Water Supply Systems Using EPANET MSX, Procedia Engineering, Volume 70, 2014, Pages 1192-1200, ISSN 1877-7058, https://doi.org/10.1016/j.proeng.2014.02.132.

Monteiro, L., et al. “Modeling of Chlorine Decay in Drinking Water Supply Systems Using EPANET MSX.” Procedia Engineering, vol. 70, 2014, pp. 1192–1200., doi:10.1016/j.proeng.2014.02.132

Newbold, Richard N., *Comparison and Simulation of a Water Distribution Network in EPANET and a New Generic Graph Trace Analysis Based Model*. Thesis. Virginia Polytechnic Institute and State University, 2009.
https://vtechworks.lib.vt.edu/bitstream/handle/10919/31177/Newbold_Thesis_ETD_v2.pdf?sequence=1&isAllowed=y

Roy, Michelle. *Investigation of Future Flow Reducer Sizes in Houses Added to an Existing Gravity Flow Water System to Ensure its Sustainability*. Thesis. University of South Florida, 2016. https://mail.google.com/mail/u/1/#search/michelle+roy+thesis/15ce4fc58787afb8?projector=1&messagePartId=0.1.

Schweitzer, Ryan W., Assessment of Sustainability of Systems Built by the National Institute of Potable Water and Peace Corps, Dominican Republic. Michigan Technological University, 2009. http://cee.eng.usf.edu/peacecorps/5%20-%20Resources/Theses/Assessment/2009Schweitzer.pdf

Schweitzer, R.W., J.R. Mihelcic, “Sustainability Analysis of Community Managed Water Systems in the Developing World,” Journal of Water, Sanitation and Hygiene for Development, 2(1):20-30, 2012.

Shapiro, S. S., and M. B. Wilk. “An Analysis of Variance Test for Normality (Complete Samples).” Biometrika, vol. 52, no. 3/4, 1965, pp. 591–611. JSTOR, JSTOR, www.jstor.org/stable/2333709.

“Statistics.” *Statistics*, by Rosie Shier, Mathematics Learning Support Centre, 2004.

Suzuki, R. *Post-Project Assessment and Follow-Up Support for Community Managed Rural Water Systems in Panama*. Thesis. Michigan Technological University, 2010. Web. 30 Nov. 2014.
http://cee.eng.usf.edu/peacecorps/5%20%20Resources/Theses/Assessment/2009Suzuki.pdf

United States, Congress, Office of Research and Developments, et al. “Water Utility Case Study Using EPANET-RTX Libraries Water Utility Case Study of Real-Time Network Hydraulic and Water Quality Modeling Using EPANET-RTX Libraries.” *Water Utility Case Study Using EPANET-RTX Libraries Water Utility Case Study of Real-Time Network Hydraulic and Water Quality Modeling Using EPANET-RTX Libraries*, 20

Watson, Sarah Louise, *Assessing the Impacts of Unrestricted Pesticide Use in Small-Scale Agriculture on Water Quality and Associated Human Health and Ecological Implications in an Indigenous Village in Rural Panama* (2014). https://usfmi.weebly.com/uploads/5/3/9/2/5392099/s_watson_assessing_the_impacts_of_unrestricted_pesticide_use_in_small-scal.pdf

APPENDIX A. NEATWORK INPUT INFORMATION BASED ON ALTO NUBE ABAJO WATER SYSTEM

Table A1. Arc list, pipe segment lengths and pipe type.

Start Node	End Node	Length (m)	Pipe*
Tank	38	37.57	2" PVC SDR 26
38	47	20.31	2" PVC SDR 26
47	49	10.16	2" PVC SDR 26
49	50	5.08	2" PVC SDR 26
50	54	20.31	1.5" PVC SDR 26
54	55	5.08	1.5" PVC SDR 26
55	56	5.08	1" PVC SDR 26
56	56.1	3.00	1" PVC SDR 26
56.1	57	2.08	1" PVC SDR 26
57	73	44.37	1" PVC SDR 26
73	86	66.01	1" PVC SDR 26
86	90	20.31	1" PVC SDR 26
90	91	5.08	1" PVC SDR 26
91	92	2.64	1" PVC SDR 26
92	93	5.08	1" PVC SDR 26
93	106	71.09	3/4" PVC SDR 21
106	114	40.62	3/4" PVC SDR 21
114	115	5.08	3/4" PVC SDR 21
115	119	20.01	3/4" PVC SDR 21
119	120	5.08	3/4" PVC SDR 21
120	121	5.08	3/4" PVC SDR 21
121	127	24.98	3/4" PVC SDR 21
127	377	110.69	3/4" PVC SDR 21
377	384	27.01	3/4" PVC SDR 21
384	Isiderio	154.44	1/2" PVC SDR 13.5"
93	XX38	134.69	3/4" PVC SDR 21
XX38	XX39	2.32	3/4" PVC SDR 21
XX39	XX43	18.29	3/4" PVC SDR 21
XX43	XX44	4.57	3/4" PVC SDR 21
XX44	XX45	4.57	3/4" PVC SDR 21
XX45	XX48	13.72	3/4" PVC SDR 21
XX48	XX49	3.72	3/4" PVC SDR 21
XX49	X29	27.91	1/2" PVC SDR 13.5"
X29	X30	3.05	1/2" PVC SDR 13.5"
X30	X42	36.58	1/2" PVC SDR 13.5"
X42	304	114.11	1/2" PVC SDR 13.5"
304	305	5.08	1/2" PVC SDR 13.5"
305	308	15.23	1/2" PVC SDR 13.5"
308	309	5.08	1/2" PVC SDR 13.5"
309	310	5.08	1/2" PVC SDR 13.5"
310	314	20.31	1/2" PVC SDR 13.5"
314	315	3.55	1/2" PVC SDR 13.5"

Table A1. (continued)

Start Node	End Node	Length (m)	Pipe*
315	316	1.73	1/2" PVC SDR 13.5"
316	317	2.33	1/2" PVC SDR 13.5"
317	317.1	5.08	1/2" PVC SDR 13.5"
317.1	319	2.03	1/2" PVC SDR 13.5"
319	327	25.59	1/2" PVC SDR 13.5"
327	328	3.55	1/2" PVC SDR 13.5"
328	331	15.23	1/2" PVC SDR 13.5"
331	333	10.16	1/2" PVC SDR 13.5"
333	Augustin	15.23	1/2" PVC SDR 13.5"
49	Cristina	3.58	1/2" PVC SDR 13.5"
49	337	3.55	1/2" PVC SDR 13.5"
337	Micaela	21.73	1/2" PVC SDR 13.5"
49	348	30.47	1/2" PVC SDR 13.5"
348	Rulfina	3.55	1/2" PVC SDR 13.5"
54	356	35.5	1" PVC SDR 26
356	358	10.16	1/2" PVC SDR 13.5"
358	Lidia	2.33	1/2" PVC SDR 13.5"
56	362	15.23	1/2" PVC SDR 13.5"
362	Benita	5.08	1/2" PVC SDR 13.5"
57	Minsdo	25.39	1/2" PVC SDR 13.5"
56.1	Julia	20.32	1/2" PVC SDR 13.5"
356	Ernesto	6	1/2" PVC SDR 13.5"
106	Choli	23.56	1/2" PVC SDR 13.5"
115	164	63.88	1/2" PVC SDR 13.5"
164	165	3.25	1/2" PVC SDR 13.5"
165	172	19.48	1/2" PVC SDR 13.5"
172	173	5.08	1/2" PVC SDR 13.5"
173	174	5.08	1/2" PVC SDR 13.5"
174	176	10.16	1/2" PVC SDR 13.5"
176	Chidtoj	44.18	1/2" PVC SDR 13.5"
121	121.1	5.28	1/2" PVC SDR 13.5"
121.1	121.2	3.55	1/2" PVC SDR 13.5"
121.2	Toman	12.69	1/2" PVC SDR 13.5"
127	Alexis	5.08	1/2" PVC SDR 13.5"
377	Rigoberto	0.66	1/2" PVC SDR 13.5"
X29	X19	24.05	1/2" PVC SDR 13.5"
X19	Herman	3.05	1/2" PVC SDR 13.5"
X29	X29.1	1.45	1/2" PVC SDR 13.5"
X29.1	X29.2	3.05	1/2" PVC SDR 13.5"
X29.2	Vicenzio	12.93	1/2" PVC SDR 13.5"
X30	Tito	4.27	1/2" PVC SDR 13.5"
X42	Beni	27.42	1/2" PVC SDR 13.5"
319	Anastasio	5.08	1/2" PVC SDR 13.5"

Table A2. Cumulative height change when water elevation is at tank overflow and nature of nodes. Nature: 0= tank, 1= node, 2= faucet.

Point	Cum Height Change Overflow (m)	x	y	faucets	nature
Tank	0	0	0	0	0
38	-10.88	0	0	0	1
47	-8.14	0	0	0	1
49	-8.87	0	0	0	1
50	-9.26	0	0	0	1
54	-11.18	0	0	0	1
55	-11.70	0	0	0	1
56	-11.92	0	0	0	1
56.1	-11.93	0	0	0	1
57	-12.15	0	0	0	1
73	-24.28	0	0	0	1
86	-31.43	0	0	0	1
90	-30.34	0	0	0	1
91	-30.67	0	0	0	1
92	-30.27	0	0	0	1
93	-30.60	0	0	0	1
106	-38.32	0	0	0	1
114	-40.68	0	0	0	1
115	-41.37	0	0	0	1
119	-44.06	0	0	0	1
120	-43.98	0	0	0	1
121	-44.09	0	0	0	1
127	-66.53	0	0	0	1
377	-71.22	0	0	0	1
384	-72.06	0	0	0	1
Isiderio	-100.18	0	0	1	2
XX38	-68.86	0	0	0	1
XX39	-68.73	0	0	0	1
XX43	-65.55	0	0	0	1
XX44	-65.74	0	0	0	1
XX45	-65.64	0	0	0	1
XX48	-66.08	0	0	0	1
XX49	-65.64	0	0	0	1
X29	-62.96	0	0	0	1
X30	-63.16	0	0	0	1
X42	-70.39	0	0	0	1
304	-100.70	0	0	0	1
305	-100.44	0	0	0	1
308	-101.05	0	0	0	1
309	-101.03	0	0	0	1

Table A2. (continued)

Point	Cum Height Change Overflow (m)	x	y	faucets	nature
310	-101.51	0	0	0	1
314	-100.70	0	0	0	1
315	-101.31	0	0	0	1
316	-100.75	0	0	0	1
317	-101.69	0	0	0	1
317.1	-101.69	0	0	0	1
319	-102.58	0	0	0	1
327	-107.53	0	0	0	1
328	-107.46	0	0	0	1
331	-108.34	0	0	0	1
333	-107.71	0	0	0	1
Augustin	-109.06	0	0	1	2
Cristina	-8.87	0	0	1	2
337	-8.85	0	0	0	1
Micaela	-11.16	0	0	0	1
348	-9.48	0	0	0	1
Rulfina	-9.94	0	0	0	1
356	-12.18	0	0	0	1
358	-12.30	0	0	0	1
Lidia	-12.25	0	0	0	1
362	-12.25	0	0	0	1
Benita	-12.33	0	0	1	2
Minsdo	-13.67	0	0	1	2
Julia	-12.37	0	0	1	2
Ernesto	-12.36	0	0	1	2
Choli	-40.78	0	0	1	2
164	-53.00	0	0	0	1
165	-53.89	0	0	0	1
172	-55.82	0	0	0	1
173	-55.85	0	0	0	1
174	-55.27	0	0	0	1
176	-55.57	0	0	0	1
Chidtoj	-58.03	0	0	1	2
121.1	-44.34	0	0	0	1
121.2	-44.34	0	0	0	1
Toman	-45.13	0	0	1	2
Alexis	-66.53	0	0	1	2
Rigoberto	-71.22	0	0	1	2
X19	-56.34	0	0	0	1
Herman	-56.47	0	0	1	2
X29.1	-62.71	0	0	0	1
X29.2	-63.03	0	0	0	1
Vicenzio	-62.34	0	0	1	2
Tito	-64.58	0	0	1	2
Beni	-73.38	0	0	1	2
Anastasio	-102.58	0	0	1	2

Table A3. Cumulative height change when water elevation is at tank outlet and nature of nodes. Nature: 0= tank, 1= node, 2= faucet.

Point	Cumulative Height Change (m)	x	y	faucets	nature
Tank	0	0	0	0	0
38	-9.38	0	0	0	1
47	-6.63	0	0	0	1
49	-7.37	0	0	0	1
50	-7.75	0	0	0	1
54	-9.68	0	0	0	1
55	-10.19	0	0	0	1
56	-10.42	0	0	0	1
56.1	-10.42	0	0	0	1
57	-10.65	0	0	0	1
73	-22.77	0	0	0	1
86	-29.93	0	0	0	1
90	-28.84	0	0	0	1
91	-29.17	0	0	0	1
92	-28.76	0	0	0	1
93	-29.09	0	0	0	1
106	-36.81	0	0	0	1
114	-39.18	0	0	0	1
115	-39.86	0	0	0	1
119	-42.56	0	0	0	1
120	-42.48	0	0	0	1
121	-42.58	0	0	0	1
127	-65.02	0	0	0	1
377	-69.72	0	0	0	1
384	-70.55	0	0	0	1
Isiderio	-98.68	0	0	1	2
XX38	-67.36	0	0	0	1
XX39	-67.23	0	0	0	1
XX43	-64.04	0	0	0	1
XX44	-64.23	0	0	0	1
XX45	-64.13	0	0	0	1
XX48	-64.57	0	0	0	1
XX49	-64.13	0	0	0	1
X29	-61.45	0	0	0	1
X30	-61.65	0	0	0	1
X42	-68.88	0	0	0	1
304	-99.19	0	0	0	1
305	-98.94	0	0	0	1
308	-99.55	0	0	0	1
309	-99.52	0	0	0	1

Table A3. (continued)

Point	Cumulative Height Change (m)	x	y	faucets	nature
310	-100.01	0	0	0	1
314	-99.19	0	0	0	1
315	-99.80	0	0	0	1
316	-99.24	0	0	0	1
317	-100.18	0	0	0	1
317.1	-100.18	0	0	0	1
319	-101.07	0	0	0	1
327	-106.03	0	0	0	1
328	-105.95	0	0	0	1
331	-106.84	0	0	0	1
333	-106.20	0	0	0	1
Augustin	-107.55	0	0	1	2
Cristina	-7.37	0	0	1	2
337	-7.34	0	0	0	1
Micaela	-9.65	0	0	0	1
348	-7.98	0	0	0	1
Rulfina	-8.43	0	0	0	1
356	-10.67	0	0	0	1
358	-10.80	0	0	0	1
Lidia	-10.75	0	0	0	1
362	-10.75	0	0	0	1
Benita	-10.82	0	0	1	2
Minsdo	-12.17	0	0	1	2
Julia	-10.86	0	0	1	2
Ernesto	-10.85	0	0	1	2
Choli	-39.28	0	0	1	2
164	-51.50	0	0	0	1
165	-52.39	0	0	0	1
172	-54.32	0	0	0	1
173	-54.34	0	0	0	1
174	-53.76	0	0	0	1
176	-54.07	0	0	0	1
Chidtoj	-56.53	0	0	1	2
121.1	-42.84	0	0	0	1
121.2	-42.84	0	0	0	1
Toman	-43.62	0	0	1	2
Alexis	-65.02	0	0	1	2
Rigoberto	-69.72	0	0	1	2
X19	-54.83	0	0	0	1
Herman	-54.96	0	0	1	2
X29.1	-61.20	0	0	0	1
X29.2	-61.52	0	0	0	1
Vicenzio	-60.84	0	0	1	2
Tito	-63.07	0	0	1	2
Beni	-71.87	0	0	1	2
Anastasio	-101.07	0	0	1	2

APPENDIX B. ADDITIONAL FIELD AND NEATWORK OUTPUT DATA

Table B1. All field observed time measurements to fill five-gallon bucket(s).

		Number of Taps Open									
Household	Measure-ment No.	**20**	**18**	**16**	**14**	**12**	**10**	**8**	**6**	**4**	**2**
	M1	203.35	210.75	208.47	206.15	199.41	189.28	183.25	185.25	178.1	158.69
Lidia	M2	211.12	211.43	209.94	208.18	196.71	191.19	184.82	184.01	180.66	157.52
	M3	211.14	209.87								
	M1	125.7	123.83	124.97	124.67	123.37	121.42	119.28	116.78	116.29	117.33
Micaela	M2	125.42	123.11	124.42	124.28	124.18	120.38	118.31	118.13	115.61	117.38
	M3	124.86	124.67								
	M1	133.31	137.47	139.44	135.38	135.78	129.88	123.78	120.69	120.6	
Ernesto	M2	134.07	137.1	139.54	136.22	135.46	130	124.16	120.16	117.71	
	M3	135.69	137.52								
	M1	105.46	193.5	184	165.62	147.98	129.5	116.9	114.64	114.82	
Julia	M2	105.4	205.03	177.1	165.2	147.16	129.59	116.14	117.87	115.38	
	M3	104.66	216.07								
	M1	125.78	99.85	100.68	100.68	100.67	96.16	95.25	92.06		
Cristina	M2	142.78	99.86	100.41	100.68	100.18	97.58	95.28	92.29		
	M3	151.94	99.47						91.22		
	M1	193.41	179.5	175.97	164.75	155.85	140.15	131.88	131.5		
Minsdu	M2	193.09	178.81	175.58	165.78	157.81	139.53	131.81	131.44		
	M3	194.56	183.13								
	M1	139.84	140.32	143.59	143.75	144.35	143.81	134.43			
Rulfina	M2	140.38	141.5	143.47	143.53	143	143.28	133.53			
	M3	140.22	142.28		143.41	144.28	142.4	136.33			
	M1	179.1	160.04	160.04	152.16	152.08	131.32	123.85			
Benita	M2	179.56	160.41	160.32	152.37	152.59	131.96	124.75			
	M3	179.03	161.53								
	M1	322.81	215.56	120.09	105.78	84.82	74.71				
Choli	M2	322.97	215.59	121.19	106.25	85.87	74.7				
	M3	333.84	234.91								
	M1	466	340.09	174.06	159.18	132.94	118.47				
Toman	M2	468.13	347.32	176.81	159.9	131.34	120.06				
	M3	472.25									
	M1	122.81	76.55	86.1	55.34	61.35					
Abundio	M2	143.06	76.59	90.72	59.79	61.94					
	M3		72.32								
	M1	215.28	130.03	138.53	89.47	86.41					
Tito	M2	213.37	132.18	137.28	90.15	85.4					
	M3	218.85	132.6	139.28	89.84	84.88					
	M1	620.65	1018.56	548.25	475.84						
Alexis	M2	618.53									
	M3										
	M1	108.9	105.43	92.37	85.88						
Chidtoj	M2	109.15	106.69	94.4	86.56						
	M3	110.62	109.9								
	M1	168.87	92.31	80.82							
Federico	M2	169.16	92.35	84.75							
	M3	169.78	92.59								
	M1	239.66	117.44	120.78							
Virginia	M2	239.65	102.22	120.25							
	M3	239.25	97.84	120.2							
	M1	126.18	128.28								
Martina	M2	127.16	130.28								
	M3	128.59	132.16								
	M1	68.03	74.44								
Roberto	M2	66.78	73.84								
	M3	66.74	74.44								
	M1	127.87									
Anastasio	M2	128.25									
	M3	127.75									
	M1	111.12									
Augustin	M2	110.03									
	M3	111.68									

Table B2. All field observed flow measurements (l/s).

		Number of Taps Open									
Household	Measurement No.	20	18	16	14	12	10	8	6	4	2
	M1	0.0931	0.0898	0.0908	0.0918	0.0949	0.1000	0.1033	0.1022	0.1063	0.1193
	M2	0.0896	0.0895	0.0901	0.0909	0.0962	0.0990	0.1024	0.1028	0.1048	0.1201
Lidia	M3	0.0896	0.0902								
	M1	0.1506	0.1528	0.1514	0.1518	0.1534	0.1559	0.1587	0.1621	0.1627	0.1613
	M2	0.1509	0.1537	0.1521	0.1523	0.1524	0.1572	0.1600	0.1602	0.1637	0.1612
Micaela	M3	0.1516	0.1518								
	M1	0.1420	0.1377	0.1357	0.1398	0.1394	0.1457	0.1529	0.1568	0.1569	
	M2	0.1412	0.1380	0.1356	0.1389	0.1397	0.1456	0.1524	0.1575	0.1608	
Ernesto	M3	0.1395	0.1376								
	M1	0.1795	0.0978	0.1029	0.1143	0.1279	0.1461	0.1619	0.1651	0.1648	
	M2	0.1796	0.0923	0.1069	0.1146	0.1286	0.1460	0.1629	0.1606	0.1640	
Julia	M3	0.1808	0.0876								
	M1	0.1505	0.1895	0.1880	0.1880	0.1880	0.1968	0.1987	0.2056		
	M2	0.1325	0.1895	0.1885	0.1880	0.1889	0.1939	0.1986	0.2051		
Cristina	M3	0.1246	0.1903								
	M1	0.0978	0.1054	0.1075	0.1149	0.1214	0.1350	0.1435	0.1439		
	M2	0.0980	0.1058	0.1078	0.1142	0.1199	0.1356	0.1436	0.1440		
Minsdu	M3	0.0973	0.1033								
	M1	0.1353	0.1349	0.1318	0.1317	0.1311	0.1316	0.1408			
	M2	0.1348	0.1337	0.1319	0.1319	0.1323	0.1321	0.1417			
Rulfina	M3	0.1350	0.1330		0.1320	0.1312	0.1329	0.1388			
	M1	0.1057	0.1183	0.1183	0.1244	0.1244	0.1441	0.1528			
	M2	0.1054	0.1180	0.1180	0.1242	0.1240	0.1434	0.1517			
Benita	M3	0.1057	0.1172								
	M1	0.0586	0.0878	0.1576	0.1789	0.2231	0.2533				
	M2	0.0586	0.0878	0.1562	0.1781	0.2204	0.2533				
Choli	M3	0.0567	0.0806								
	M1	0.0406	0.0556	0.1087	0.1189	0.1424	0.1597				
	M2	0.0404	0.0545	0.1070	0.1184	0.1441	0.1576				
Toman	M3	0.0401									
	M1	0.1541	0.2472	0.2198	0.3420	0.3085					
	M2	0.1323	0.2471	0.2086	0.3165	0.3055					
Abundio	M3		0.2617								
	M1	0.0879	0.1455	0.1366	0.2115	0.2190					
	M2	0.0887	0.1432	0.1379	0.2099	0.2216					
Tito	M3	0.0865	0.1427	0.1359	0.2107	0.2230					
	M1	0.0305	0.0186	0.0345	0.0398						
	M2	0.0306									
Alexis	M3										
	M1	0.1738	0.1795	0.2049	0.2204						
	M2	0.1734	0.1774	0.2005	0.2186						
Chidtoj	M3	0.1711	0.1722								
	M1	0.1121	0.2050	0.2342							
	M2	0.1119	0.2049	0.2233							
Federico	M3	0.1115	0.2044								
	M1	0.0790	0.1611	0.1567							
	M2	0.0790	0.1851	0.1574							
Virginia	M3	0.0791	0.1934	0.1574							
	M1	0.1500	0.1475								
	M2	0.1488	0.1453								
Martina	M3	0.1472	0.1432								
	M1	0.2782	0.2542								
	M2	0.2834	0.2563								
Roberto	M3	0.2836	0.2542								
	M1	0.1480									
	M2	0.1476									
Anastasio	M3	0.1481									
	M1	0.1703									
	M2	0.1720									
Augustin	M3	0.1695									

APPENDIX C. STATISTICAL METHODS, EQUATIONS, AND RESULTS USED IN DATA ANALYSIS

In order to calculate the standard error of the mean difference, SE (d,) the following formula. Equation 7, is used:

$$SE\ (\bar{d}) = \frac{s_d}{\sqrt{n}} \qquad (6)$$

where,

$s_d = standard\ deviation\ of\ the\ differences$
$\bar{d}$ = mean difference
n= sample size

In order to calculate the t-statistic, T, the following formula, Equation 8, is used:

$$T = \frac{\bar{d}}{SE\ (d)} \qquad (7)$$

Table C1. Standard deviations for differences between field measured flow and Neatwork simulated flow by varying number of open taps.

Tap Household	Std. Deviation
Lidia	0.0038
Micaela	0.0022
Ernesto	0.0031
Julia	0.0117
Cristina	0.0051
Minsdu	0.0023
Rulfina	0.0039
Benita	0.0049
Choli	0.0092
Toman	0.0258
Abundio	0.0406
Tito	0.0047
Alexis	0.0258
Chidtoj	0.0054
Federico	0.0229
Virginia	0.0155
Martina	0.0038
Roberto	0.0196
Anastasio	N/A
Augustin	N/A
Average	**0.0117**

Table C2. Standard deviations for differences between field measured flow and Neatwork simulated flow by varying tap house locations.

Taps open	Std. Deviation
20	0.0397
18	0.0402
16	0.0431
14	0.0448
12	0.0220
10	0.0238
8	0.0222
6	0.0253
4	0.0301
2	0.0401
Average	**0.0331**