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PLANNING FOR INTERMITTENT WATER SUPPLY IN SMALL GRAVITY-FED DISTRIBUTION SYSTEMS: CASE STUDY IN RURAL PANAMA

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By

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List of Abbreviations

CWS	Continuous Water Supply
DISAPAS	Dirección del Subsector de Agua Potable y Alcantarillado Sanitario
EPA	Environmental Protection Agency
GPCD	Gallons per Capita per Day
IDAAN	Instituto de Acueductos y Alcantarillados Nacionales
IWS	Intermittent Water Supply
JAAR	Junta Administrativo de Acueductos Rurales
JMP	Joint Monitoring Program (for Water Supply and Sanitation)
LPCD	Liters per Capita per Day
LPD	Liters per Day
LPS	Liters per Second
MINSA	Ministerio de Salúd de Panamá
NWRI	National Water Research Institute
SWMM	Storm Water Management Model
UN	United Nations

Abstract

Intermittent water supply (IWS) is defined as a piped water distribution system that operates in an intermittent fashion, i.e. less than 24 hours per day. Piped water distribution systems are designed to operate with continuous water supply (CWS), meaning the system is operated continuously and maintains positive pressures in the distribution network. Operating a system in an intermittent fashion can cause inequality of access in a water distribution system. It may also result in lower water quality and wear and tear on the system.

In the community of Espavé, Panamá a new water system was installed and brought online in 2015. It was designed to operate continuously; however, during the dry season the flow from the spring source drops below the total daily demand of the community. Under this intermittent regime, the system operates differently, causing some community members not to receive water service.

Survey and design data were used to model the system, as designed, in EPANET for CWS operation and EPA SWMM for IWS operation. Various trial runs were conducted in SWMM using dynamic flow routing to simulate dry season flow rates, under average and high demand. The model was then divided into two sections in order to isolate higher households from those at lower elevations. These isolated sections were used to develop a staggered operation system for water delivery.

Model results indicate that reducing daily usage during the dry season is recommended to prevent intermittency in the system. If demand continues to exceed supply, staggering the delivery to different areas may help to maintain equality in distribution. In the future models for water distribution systems should be developed to simulate IWS.

1 Introduction

In 2010 the United Nations recognized water as a human right and called upon States and international organizations to make clean safe water available to all (UN, 2014). Access to clean water is an important issue for the future, and meeting demands will become increasingly difficult in both the industrialized, and developing world. Climate change, groundwater overdraws, and increased agricultural and industrial water use are all drivers that will affect access in the future.

In industrialized nations, such as the United States, technology is likely to be able to meet the needs of most of its water users. In Carlsbad, California, a 50-million gallon per day desalination plant just came on line (Carlsbad Desalination Project, 2017). Whereas desalination was previously considered economically unfeasible, dryer and more affluent parts of the world are beginning to utilize these technologies. States are also beginning to change their laws in favor of direct potable reuse, another technology driven approach to expanding and increasing the reliability of supply (NWRI, 2017).

In developing nations, advanced water treatment and supply solutions may be found in large cities where economies of scale can justify the expense. Peri-urban and rural communities, however, depend on more traditional water sources to meet their needs. In Panamá, small and large systems are managed by two different agencies. Systems serving less than 1,500 people are managed by the Dirección del Subsector de Agua Potable y Alcantarillado Sanitario (DISAPAS), and larger systems are managed by the Instituto de Acueductos y Alcantarillados Nacionales (IDAAN) (Panamá).

1.1 Panamanian Water Institutions

While IDAAN functions as a public utility in which they provide service for payment, DISAPAS a subsector of the ministry of health (MINSA), functions on a model more recognizable in the developing world. The function of DISAPAS is to act as an organizer for policies regarding rural aqueducts, and although MINSA is sometimes involved in the construction of systems, they do not directly manage them. The direct management of a community's aqueduct resides with the Junta Administrativo de Acueductos Rurales (JAAR), a committee of 7 community members tasked with the operation and maintenance of a system, or multiple systems within their community (MINSA, 2017).

The JAAR system in Panamá has both positive and negative aspects. It allows for community members to work with outside groups to fund and construct aqueduct systems that are often located in remote areas, and might otherwise be overlooked. These localized water committees can be empowering and work well when a community has strong internal leadership, and when water resources in the community are sufficient to meet demand. Many communities, however lack the leadership and community engagement to effectively manage and maintain these systems. In many communities there are high rates of delinquency in payment of water bills. Lack of funds or poor money management; also often leads to system deterioration, and sometimes an indefinite shutdown of the system.

1.2 Intermittent Water Supply

Many of the rural aqueducts in Panamá operate intermittently because of community mismanagement or because the water supply source is insufficient to meet demand. This is common throughout Latin America and the developing world. It is estimated that one-third of people in Latin America and Africa, and more than one-half in Asia, have intermittent water supplies from piped networks (Kumpel & Nelson, 2016). While water distribution networks are designed for continuous water supply (CWS), intermittent water supply (IWS) is defined as occurring when a piped water network operates less than 24 hours a day (Faure & Pandit, 2017).

1.2.1 Causes and Behaviors related to IWS

IWS can be caused by a range of factors including insufficient water resources, growth of a system beyond its initial design parameters, poor management, and user behavior. Broad distribution (e.g., number of households served) is commonly seen as an indicator of access to water delivery, and thus is very popular politically. However, without sufficient supply, quality of delivery can be overlooked (Galaitsi et al., 2016). For example, in 2012 the UN Millennium Development Goal target to halve the proportion of people without access to improved drinking water sources was met early. However, the reliability and quality of these sources was not considered (JMP, 2012). Prioritizing broad distribution can have negative effects such as water rationing, reducing prices, and is also a cause of IWS (Galaitsi et al., 2016). Further, operators who are not properly trained can cause IWS in a system. Some common misconceptions among operators are that pressure in the system can cause wear and tear on the tubes, water systems provide equitable distribution, and that IWS can provide more time for maintenance and repairs (Cabrera-Béjar & Tzatchkov, 2012).

Water users in an IWS system often develop poor habits because of perceived scarcity. For example, users with more access than others will often withdraw and store more than is needed (Cabrera-Béjar & Tzatchkov, 2012). This leaves others, in parts of the system with lower pressure, with less access, which in turn increases the perception of scarcity. A common practice for water users in an intermittent system is to leave the tap open, both when there is no water and when it is running (Cabrera-Béjar & Tzatchkov, 2012). Even when a system is expanded to provide continuous flow, some of these behaviors might continue. These scarcity rationing behaviors can be self-reinforcing, causing intermittency to persist. These behaviors could be the last thing to be resolved, as user perceptions are slow to change (Galaitsi et al., 2016).

1.2.2 Effects of IWS on Water Quality

Maintaining continuous positive pressure is an important factor in preventing contamination in a water distribution network (Kumpel & Nelson, 2014). Lack of positive pressure, and frequent starting and stopping of a system can cause wear and tear on pipes and other system components. When starting an IWS system, pipe scouring, negative pressures, air and sediment blockages, and pipe bursts can occur. This can lead to contamination through sloughing of biofilms, backflow, or resuspension of particulate matter (Kumpel & Nelson, 2014). Leaks in IWS systems are common and also offer intrusion pathways for contaminants (Kumpel & Nelson, 2016).

IWS has been recognized for its contaminant pathways as far back as 1874, when the *British Medical Journal* gave the account, "Intermittent water supply had become a source of grievous danger to health by the suction action in the water-pipes during the intervals of filling, which sucked into the water, through local defects in the pipes, polluted surface-water and fluid-sewage" (Br Med J, 1874). IWS has been linked to infectious hepatitis and diarrheal diseases such as amebiasis, typhoid, and cholera (Kumpel & Nelson, 2016). A study of children under the age of five in Hubli-Dharwad India, did not find that IWS was associated with diarrheal disease, but researchers conceded that their findings could reflect other contaminant pathways from household water storage (Ercumen et al., 2015; Mellor, Smith, Amidou, & Dillingham, 2013). Furthermore, a study in Arraiján, Panamá found that chlorine residuals were effective in helping to meet water quality standards in intermittent water systems, but that drinking "first flush" water should be avoided (Erickson, Smith, Goodridge, & Nelson, 2017).

2 Purpose

Because of the commonality of IWS in water distribution systems in the developing world, it is important to consider how systems should be designed, maintained and operated either to ensure CWS or to mitigate the negative effects of IWS. This study looked at a recently built system in the community of Espavé, Panamá. During the dry season, flows in the spring source decrease, and the system is forced to operate under IWS conditions. This causes inequality in the community because water is distributed differently when operated under IWS conditions. Members of the community that live at higher elevations may not receive water service during the time of year when the system is operated intermittently.

The objective of this case study was to model the system under both CWS and IWS conditions to better understand the effects of IWS operation, and to offer possible technical and behavioral solutions for systems that operate in this manner.

Data from the original Espavé water system design were used to create a model using EPANET 2.0 (Rossman, 2008). This model was used to analyze the systems operating conditions under CWS operation. A second model was then created in EPA SWMM 5.1 (Huber, 1985; Rossman, 2015). This model was used to analyze water distribution characteristics during IWS operation of the system.

Three scenarios were created using flowrate data from the Espavé water supply. The first scenario simulated supply that was low but sufficient to meet demand. The second scenario represented an intermediate condition in which supply that was sufficient to meet demand but still above the lowest measured flowrate. The third scenario represented the lowest measured supply. The model was then used to evaluate operating scenarios that might improve equality of service for the community of Espavé.

3 Background

The community of Espavé, with cooperation from Peace Corps volunteer Jessica Glenn completed construction of a new aqueduct in October of 2015. The system, designed by Glenn, now serves 22 families in the community that previously did not have access to an improved water source. The aqueduct was originally designed for 27 households using NeatWork (Babonneau, Corcos, Drouet, & Vial, 2010). NeatWork is a software program developed by the NGO Agua Para la Vida and Logilab specifically for gravity-driven water distribution networks. What differentiates NeatWork from EPANET is that its design parameters are pressure driven as opposed to demand driven. However, like EPANET, the model is dependent on CWS (ORDECSYS, 2010).

During the subsequent two years of operation, the system was observed to operate as designed for most of the year. However, there was a period of time during the first dry season when the system was operated under IWS conditions. During a period of one to two months in 2016, the system was only operated for a period of several hours each morning, and then shut down to allow for the tank to refill. One family, located at the upper elevations of the system, reported not receiving water during this entire period, but it is reasonable to believe that other families were also affected.

3.1 Espavé

Espavé is located in the *corrigimiento* (similar to a township) of Cerro Caña, in the district of Müna, region of Kädriri, in the Comarca Ngäbe-Buglé, Panamá. It is a small community of 27 households, on the outskirts of the larger community of Las Trancas, where the children attend primary school. The majority of community members are Evangelical Christians, and attend the community church. The community members are organized into committees which include the JAAR that manages the water system and an artisan group that makes *naguitas*, doll sized versions of the traditional dress that Ngäbe women wear. They also attend Padres de Familia, which is the parent-teacher association in Las Trancas. Figure 3.1 shows the location of the community of Espavé in Panama.

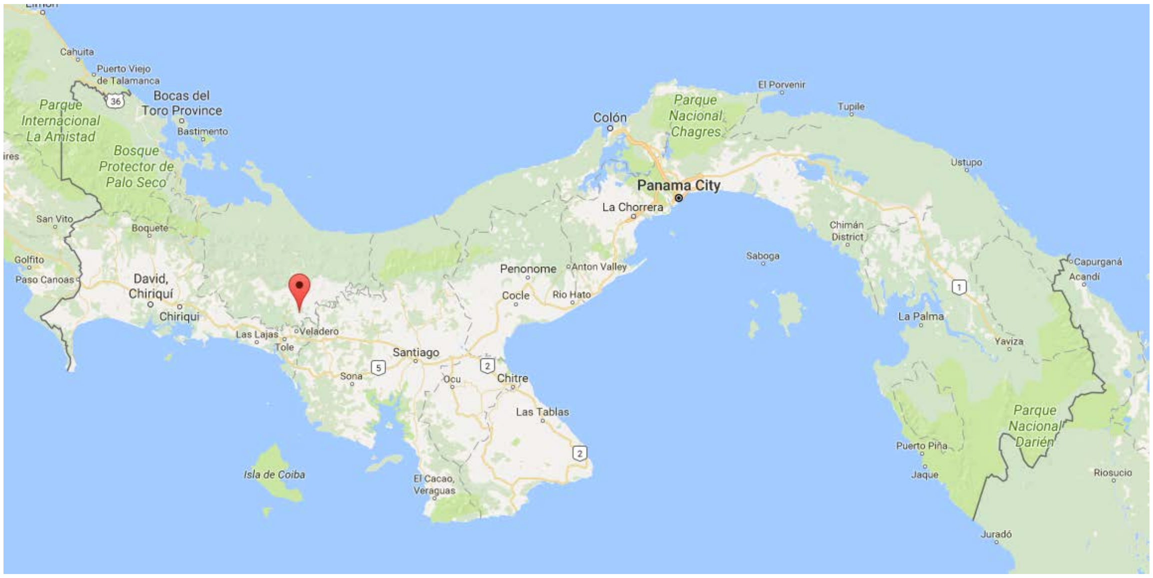

Figure 3.1. Map of Panamá. Image Source: Google Maps. See Appendix A for full attribution and copyright licensing information.

3.2 Seasonal Precipitation Patterns

In Panamá there are two seasons, which are defined by precipitation, rather than temperature. *Verano* or summer is a period of dry weather, and *invierno* or winter is a period of wet weather. Seasons are often a matter of perception in Panamá. Summer might be considered a dry hot afternoon during an otherwise wet time of year, or even a short period of drought. Winter is any time there is significant rainfall, no matter the time of day or year.

Precipitation patterns differ throughout the country, so while in many areas of the Pacific coast of Panamá there are more extended periods of drought, in the Bocas del Toro region of the Caribbean coast there is consistent rainfall with periodic brief periods of drought. The southeastern region of the Comarca Ngäbe-Buglé, known as Kädriri, has an extended dry season that typically lasts from the middle of December through the middle of April. During this time, there is little to no precipitation, and water sources such as springs and streams lose flow and, in some cases, completely dry up. At the end of April, the rains return, and the water sources rapidly recover their flow.

3.2.1 Climate Change

In Panamá climate change is a widely accepted phenomenon, and not as controversial as in the United States. Anecdotally, many Panamanians believe that the climate in Panama is changing. Those who live in areas where there are distinct wet and dry seasons, note that the rains have been arriving later than usual in recent years. Heavy rains that once arrived in April, now arrive in June.

Climate modeling may support these observations. For example, one study showed a distinct drying pattern in the Central American region, where the driest periods occurred during the months of June and July. These models, however, are far from conclusive, and more work needs to be done to reduce uncertainty in the findings (Hidalgo, Amador, Alfaro, & Quesada, 2013).

Figure 3.2 shows annual rainfall data collected at three meteorological stations near Espavé (Cedeñor & Navas, 2017). The trend line shows an increase in rainfall from 1992 to 2015. This, of course, does not mean that the accounts of local Panamanians are not true. While total annual rainfall is increasing, it is possible that it is a reflection of more precipitation during the rainy season, and that the rainy season is occurring later in the year. It would be necessary to look at precipitation data for May, June, and July to see this shift. This is important because the effects of a longer dry season likely would not be mitigated by increased rainfall in the wet season.

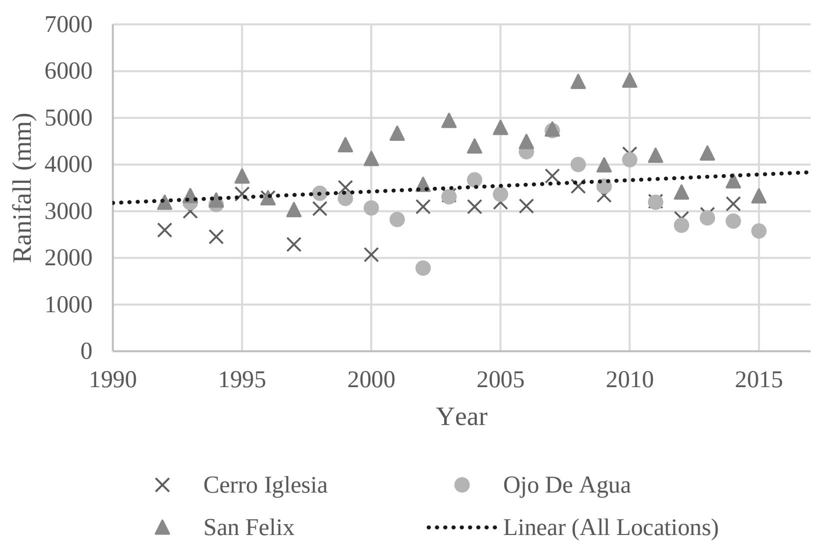

Figure 3.2. Annual Rainfall from Meteorological Stations near Espavé.

3.3 Water Use Behavior

In order to obtain the funding to build the water system in Espavé, JAAR members were required to attend a seminar that taught them how to maintain and manage the system, and instill good water use habits. These seminars are administered over the course of several days or weeks depending on scheduling and what works best for the community and cover system maintenance, roles of water committee members, teamwork, basic accounting concepts and Panamanian laws that pertain to the management of an aqueduct. Unfortunately, not all community members are required to attend. However, many of the community members picked up these skills while working on the aqueduct and interacting with Peace Corps volunteers. In addition, a paid community technician has been charged with routine maintenance of the system. This person organizes community work days, and fixes small issues as they arise, taking much of the pressure off of committee members.

While the system is running under CWS conditions it should be relatively easy to maintain these good habits. Under IWS conditions, however, it will be more difficult. There are many systems that have been built in the Comarca Ngäbe-Buglé and other rural areas of Panamá that have degraded from CWS to IWS operation regimes over time (Suzuki, 2010). Users in these systems often exhibit behaviors related to intermittent operation that can cause further inequity in the system. There are also many cultural behaviors that will affect how the system operates. Most of these behaviors are related to perceived water scarcity in the system.

3.3.1 Waste

There are many cultural norms that can lead to wasting water in rural water systems in Panamá. One of the most common things observed in IWS systems was that taps would be left open, including when the water was running. In this manner people can tell when there is water available. It is also common to do laundry under running water. Although washing machines are common in most urbanized areas of Panama, many Panamanians wash clothes by soaking them with soap, slapping them on a rock, and rinsing them under running water. It is also common to leave the water running while bathing.

In rural aqueducts, it is common for the residents to be responsible for the tube leading from the system to their house. In many cases this tube is not buried deeply enough, or not at all. These tubes deteriorate more quickly and can also be damaged by livestock. It is common for these tubes to leak, and they often take longer to replace because it is the responsibility of the owner, and not the water committee, to replace them.

3.3.2 Storage

In most parts of Panamá, it is common to keep water stored in five gallon containers, called *cubos* or *galones*, depending on the type of storage vessel. This is because even in more reliable systems the water sometimes goes out, and it is good to have water available during these times. In more unreliable IWS systems, often the first thing done when the water comes on is to fill these storage vessels. Some people have 55 gallon drums that they use to store water, but in the Comarca, these drums are mostly used for rainwater collection. Many of these containers lack caps or lids, and are stored on the ground where they can be easily contaminated.

3.4 Water Quality

Rural aqueducts are required to have treatment, which often is in the form of an in-line chlorinator. The community of Espavé installed an in-line chlorinator shortly after the system went on-line. Chlorine tablets are obtained from the Ministry of Health, and are administered according to the size of the storage tank. In an intermittent system, this can be an issue because the volume of water in the tank decreases with time, and residence time can be greatly decreased if the system is not given a chance to recover. Maintaining CWS is important for allowing the chlorine in the system enough time to inactivate any pathogens that have entered the system. Further, continuous positive pressure in the distribution network prevents pipe degradation and opportunities for contaminants to enter the system.

3.5 Topography

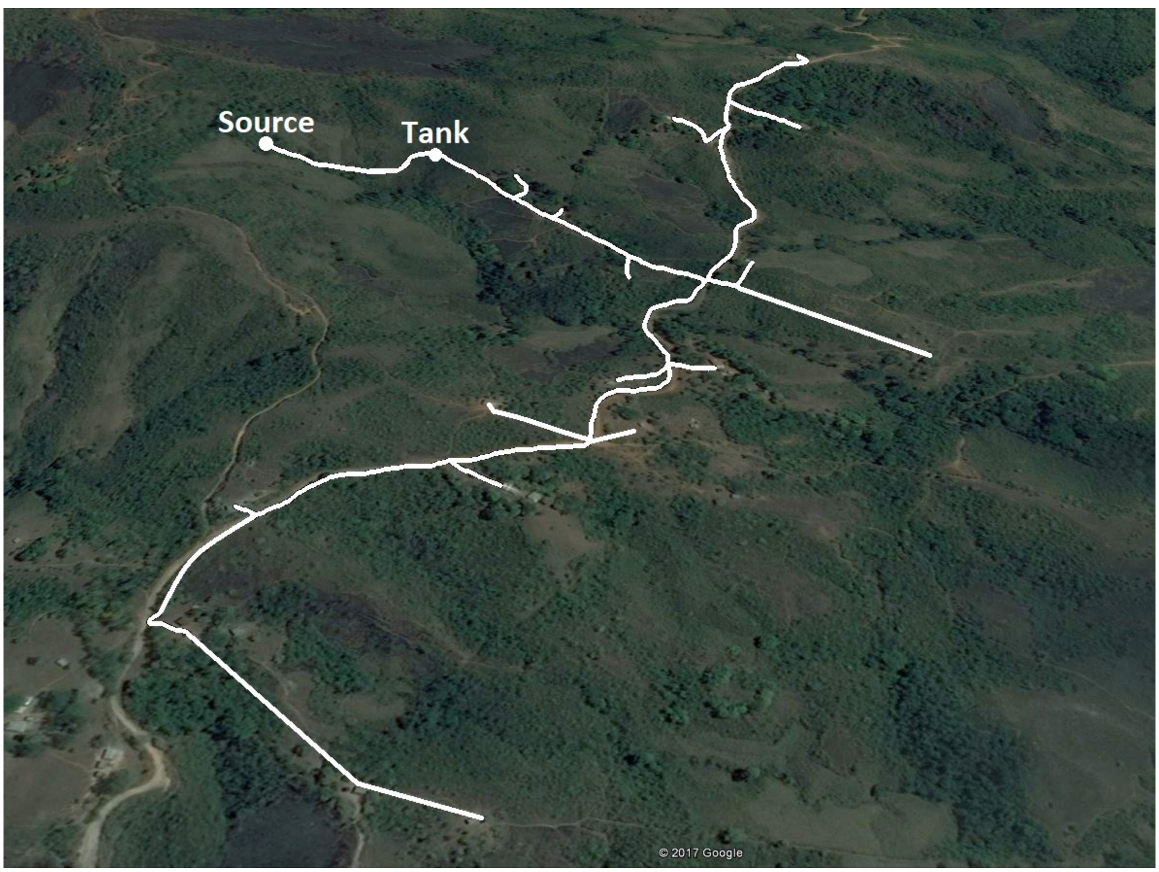

Figure 3.3 Espavé Water Distribution System Topographic Overlay. Image Source: Google Earth, See Appendix A for full attribution and copyright licensing information.

Figure 3.3 shows the topography of the community of Espavé with an overlaid diagram of the water distribution network. The spring source (*ojo*) and tank, which are labeled, are located close to one another at the highest elevation point in the community. From the tank, the three inch main line drops 50 meters in elevation to the main intersecting junction of the system. From the main intersection, the three inch main branches to the northeast increasing in elevation until it reaches its northern terminus. The elevation at this location is approximately four meters below the level of the tank. The main line of the southern branch of the system is reduced to 1.5 inches. It descends in elevation and then climbs to a level 17 meters above the main junction. At this point the tube size is again reduced to 0.5 inches and the line descends to its terminus approximately two meters below the level of the main junction. The eastern branch of the main line is reduced to 0.5 inches and drops another 15 meters in elevation before reaching its terminus. This is the lowest point of the system, approximately 65 meters below the level of the tank.

4 Methods

In order to evaluate the water distribution system in Espavé, it was necessary to create a model of the system in both EPANET and EPA SWMM. The EPANET model was used to simulate steady-state and demand-driven pressures and flow rates in the system while operating under CWS conditions. The SWMM model was developed to try to simulate transient, pressure-driven conditions in the system, while it was operating under IWS conditions.

4.1 Measured Flowrates

Flowrates were measured at each household in Espavé on November 6, 2015, shortly after the system was completed. November is the last full month of the rainy season in Espavé, so at the time of measurement the system was operating under CWS conditions. As seen in Figure 4.1, during the inspection of the system several leaks were observed, and these were reported to the operator to be repaired. Also at the time of measurement, there was one community member observed withdrawing water. Leaks and water use could have contributed to lower pressures in the system at the time of measurement.

Figure 4.1. Leaks Observed during Inspection of the Espavé Water System on November 6, 2015. Clockwise from Top Left: Reduction Leading to P10 spraying water; Leak at Junction N9 Wrapped in Plastic; Air Release valve under high pressure spraying water. (Photos by author)

The measured flowrates were used in the SWMM analysis (described below) to calculate the smallest volume per capita that would be available at the tap (Table C.1). Flowrates were not used to validate results in either the EPANET or EPA SWMM models, which represent the system as designed. Table 6.1 in Appendix C lists measured flowrates for each household.

4.2 EPANET

EPANET is a hydraulic modeling software developed to model pressurized water distribution systems (Rossman, 2000). It is widely used for modeling CWS systems, and can be very useful for simulating hydraulic and water quality behavior within pressurized networks (Rossman, 2000). Because the system was designed for continuous operation, it makes sense to begin analysis of this system using EPANET to establish that it will function as designed under normal flow conditions, and predict the minimum flowrate required to maintain a CWS.

The original design data that were used to model the system included tank size and elevation, node elevation, pipe length and diameter, and pipe material (roughness). The system also included flow reducing discs, which serve to reduce flow rates in parts of the system that have very high pressures (Drake, 2015). All of the data that was used in the model came from Jessica Glenn's design spreadsheet for Espavé. Further information on the system, and how it was designed, can be found in her WaterSTAR design report (Glenn, 2014). Figure 4.2 shows the schematic of the model with households listed.

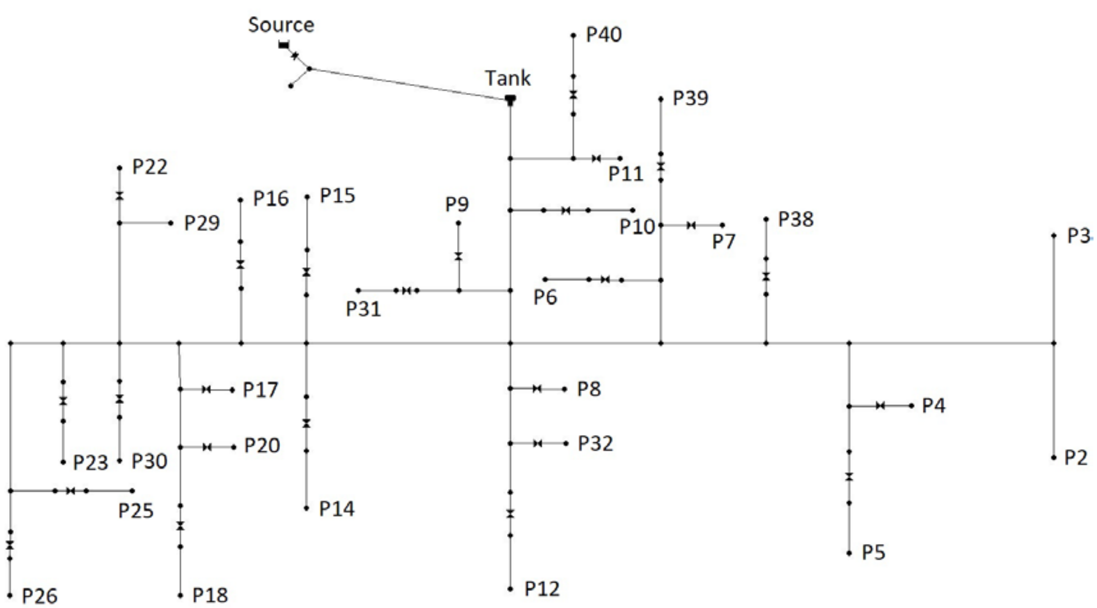

Figure 4.2. EPANET Schematic of Espavé.

4.2.1 Model Development

The model was constructed by following instructions in the EPANET 2.0 manual (Rossman, 2000). Flow was modeled in liters per minute. Head loss in the pipes was determined using the Hazen-Williams formula, which is the convention in the U.S. The Hazen-Williams formula was originally developed for turbulent flow (Rossman, 2000), which is expected in water distribution systems when water is being withdrawn. The required inputs include a dimensionless Hazen-Williams roughness coefficient C, which is 150 for PVC pipe (The Engineering Toolbox, 2017).

Flow from the source was modeled using a reservoir and a false node. A check valve was placed on a short pipe between the reservoir and the junction node that represents the location of the sources. This approach was used to simulate overflow from the reservoir. The false node was used to assign a negative base demand equal to the flowrate from the spring source. This modeling approach prevents more flow from the reservoir than the spring can actually provide, while maintaining realistic pressures on the line from spring to tank. Seasonal flowrates were obtained from the design spreadsheet provided by Jessica Glenn.

4.2.2 Flow Reducing Discs

There is not a mechanism in EPANET designed specifically to model flow reducing discs, also known as orifices. In order to model the effect of flow reducing discs on the system throttle control valves were used. Throttle control valves were used to represent orifices because they use a minor head loss coefficient to model how much a valve is closed (Rossman, 2000), which is most representative of how a flow reducing disc works.

In most cases minor loss coefficients can be found in text books; however, there are no standard coefficient listings available for orifices. Drake (2015) however, found that a head loss coefficient θ of 0.68 was a best fit for measured losses due to flow reducing discs. In order for this to be useful, the coefficient (θ) used in NeatWork had to be converted to a coefficient, K, which is used in EPANET. Equation 4.1 shows the head loss equation using θ as the coefficient in NeatWork (Drake, 2015).

Equation 4.1

$$\partial h = -\theta \frac{Q^4}{d^4}$$

Where ∂h is the head loss (m), Q is the flowrate (m^3/s), and d is the pipe diameter (m). Equation 4.2 shows the head loss equation for throttle control valves using K as the coefficient in EPANET (Rossman, 2000).

Equation 4.2

$$h_L = K\left(\frac{v^2}{2g}\right)$$

Where h_L is the head loss (m), v is the velocity (m/s), and g is acceleration due to gravity. By setting the head loss equations equal to each other, it was found that the equivalent K for minor losses was 2.62.

4.2.3 Patterns

In EPANET it is possible to model water use patterns, based on an average hourly demand at each outlet node. For this system, each household was assigned an average daily demand in liters per minute. The UN recommended domestic water use for good health outcomes is 50 liters per capita per day (LPCD), and this was the volume used to calculate daily demand (Howard & Bartram, 2003). The daily demand at each node differed depending on family size, which was available from Jessica Glenn's WaterSTAR.

Based on observation, a daily water use pattern was specified to simulate water use in the community over a 24-hour period. A multiplier was assigned for each hour of the day, and the average of all of the multipliers was equal to one, so that the total assigned daily demand was achieved at each tap (see Figure 4.3). For example, for a family of 6, the baseline multiplier of 0.48 yields six LPH in each tap, while the peak multiplier for the early morning of 1.92 yields 24 LPH, per tap.

By using these multipliers, it was possible to get a better representation of the demands on the system throughout a 24 hour period. The peak demand shows how the system operates at high water use times. Pressure drops in the system show which users are most affected by high peak demand.

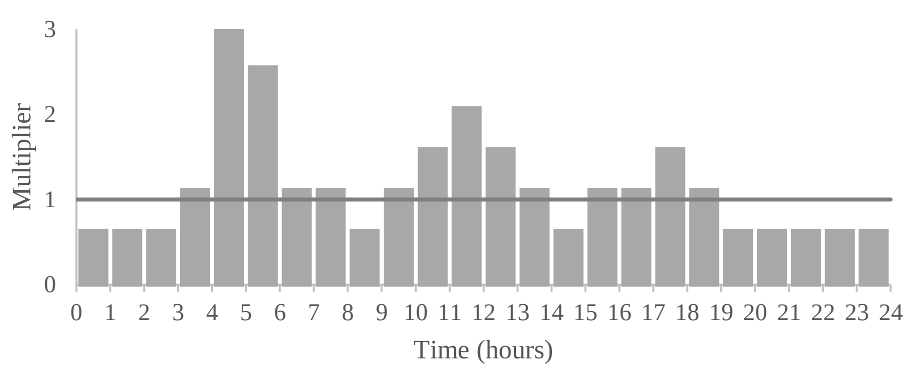

Figure 4.3. Daily Demand Pattern for Espavé.

4.3 EPA SWMM

EPA SWMM is a hydraulic modeling software generally used for analysis of open channel systems such as storm drains and sewers (Rossman, 2015). However, SWMM has been used to model non-steady-state conditions for the analysis of pump driven water distribution systems (Kabaasha, 2012; Shrestha & Buchberger, 2012). Although SWMM is not designed for modeling water distribution systems, its capabilities allow for a better understanding of how these systems will behave under IWS conditions. During the start-up period of an intermittent system, water flows through empty pipes and gradually fills them until the entire system is pressurized. Once the system is fully pressurized, it can be better represented in EPANET. However, it is of great value to know how the system will operate up to this point.

It is not possible to import an EPANET file directly into SWMM with standard software. Therefore it was necessary to build a new model of the system in SWMM. Most of the components in EPANET can be represented in SWMM, although the terminology used in SWMM is different in some cases, and in other cases the components function differently. The design choices made for EPANET and SWMM are given in Table 4.1

Table 4.1 Comparison of Tools and Inputs Used in EPANET vs. EPA SWMM

	EPANET	**EPA SWMM**
Source	Reservoir connected to a false node (elevation, negative base demand)	Direct inflow into the tank (inflow)
Tank	Tank node (elevation, initial & max level, diameter)	Reservoir (elevation, initial & max depth, surface area)
Nodes	Junction node (elevation, base demand)	Junction Node (elevation, negative base inflow)
Pipes	Pipe (length, diameter, Hazen-Williams roughness)	Force main (length, max depth, Hazen-Williams roughness)
Flow Reducing Discs	Throttle control valve (diameter, loss coefficient derived for flow reducing discs (Drake, 2015))	Side facing orifice (height, default loss coefficient retained from SWMM model)

The SWMM model was set up to mirror the EPANET model visually, and the data used in the set up were obtained directly from the EPANET model (see Figure 4.4). Only the location of the flow reducing discs was moved, so as not to affect the slope of the pipes, but this is not expected to significantly affect the model results.

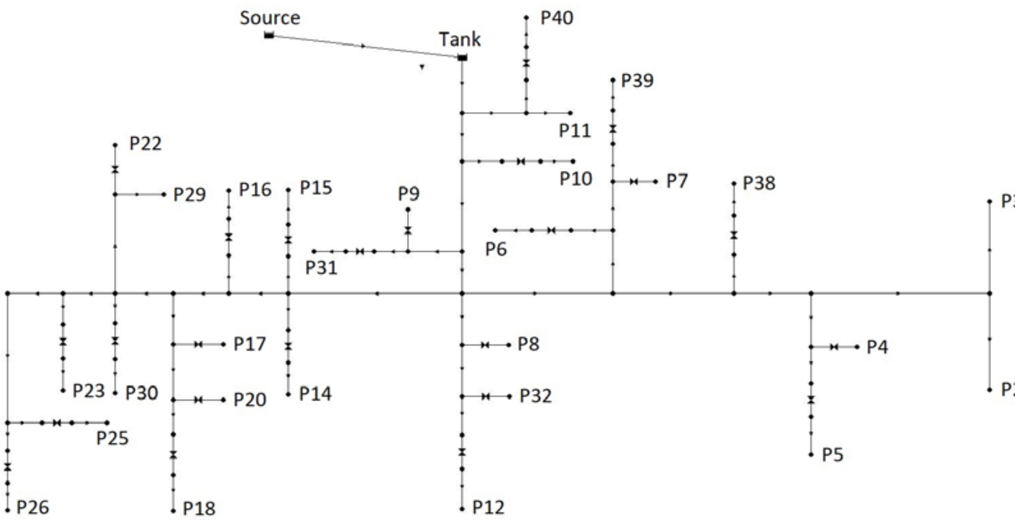

Figure 4.4. SWMM Model Schematic. Numbered nodes represent households in the Espavé system.

4.3.1 Dynamic Wave Routing

SWMM uses dynamic wave routing to model pressurized systems such as force mains. Dynamic wave routing solves the complete Saint Venant equations, including continuity and momentum equations for the conduits and continuity at the nodes. In addition to pressurization it can account for channel storage, backwater, entrance and exit losses, and flow reversal. It is also appropriate for modeling restrictions such as the orifices that are used to represent flow reducing discs in the model (Rossman, 2015). Table 4.2 shows the settings used for dynamic wave routing.

Table 4.2 Simulation Options for Dynamic Wave Routing

Simulation Options – Dynamic Wave	
Inertial Terms	Dampen
Normal Flow Criterion	Slope and Froude
Force Main Equation	Hazen-Williams
Variable Time Step Adjustment	75%
Minimum Variable Time Step (sec)	0.5
Time Step for Conduit Lengthening (sec)	0.52
Minimum Nodal Surface Area (m^2)	0.001
Maximum Trials per Time Step	8
Head Convergence Tolerance (m)	0.0015

Setting the routing time step to 0.5 seconds minimized continuity error in the model. The minimum variable time step and the time step for conduit lengthening were also set at 30 seconds. The minimum nodal surface area was reduced to $1x10^{-3}$ m^2, and the head convergence tolerance was set to $1.5x10^{-3}$ m.

4.3.2 Nodes

In SWMM, nodes are modeled as manholes. In order to be representative of the junctions in a water distribution system, the maximum height of each node was given as the inner diameter of the pipe at each junction. At junctions where pipes of two different diameters meet, the inner diameter of the larger pipe was used. It was also necessary to set the surcharge depth of each node above the hydraulic grade line. Otherwise, the model would simulate surface flooding conditions resulting in water loss at each node. An outfall was necessary for the model to run, although it was unnecessary to attach the outfall node to the rest of the network with a link. The elevation for that outfall was set at the maximum elevation of water in the tank.

4.3.3 Pipes

The pipes were represented in the model as force mains. Similar to the pipes in EPANET, they were given a Hazen-Williams coefficient to model friction losses along the length of the pipe. The lengths and inner diameters of the pipes were identical to those in the EPANET model, as were the Hazen-Williams roughness coefficients.

4.3.4 Flow Reducing Discs

In SWMM, flow discs can be represented as side-facing orifices. The height of the orifice was given as the opening size in a given flow disc. The invert elevation was set equal to the invert elevation of the inlet node. The default discharge coefficient (0.65.) was used.

4.3.5 Source and Tank

The Espavé tank was modeled as a reservoir in SWMM. The same maximum depth input was used for both models. The volume of a reservoir was calculated based on a functional curve relating surface area to depth. Equation 4.3 was used to caluclate the surface area of the reservoir (Rossman, 2015).

Equation 4.3

$$Area = A \times Depth^B + C$$

Where A is the free surface of the tank, and is equal to 12.46 m^2; B is an exponent that calculates the functional curve of the reservoir related to the depth and was given a value of 0; and C is a constant that was also given a value of 0.

A reservoir was also chosen to represent the water source. The coefficient A was set to a value of 1.5 to represent the free surface of a small spring box. The invert elevation was 6.02 meters above the elevation of the tank. An inflow was specified to represent flow from the source to the tank.

4.3.6 Supply

As seen in Figure 4.5, the transition from rainy season flow to dry season flow is gradual. In 2015, Panamá was suffering from a drought, so the average flow was likely lower than during non-drought years. With more years of data, the average would most likely be higher and the peak of the dry period would likely shift toward April.

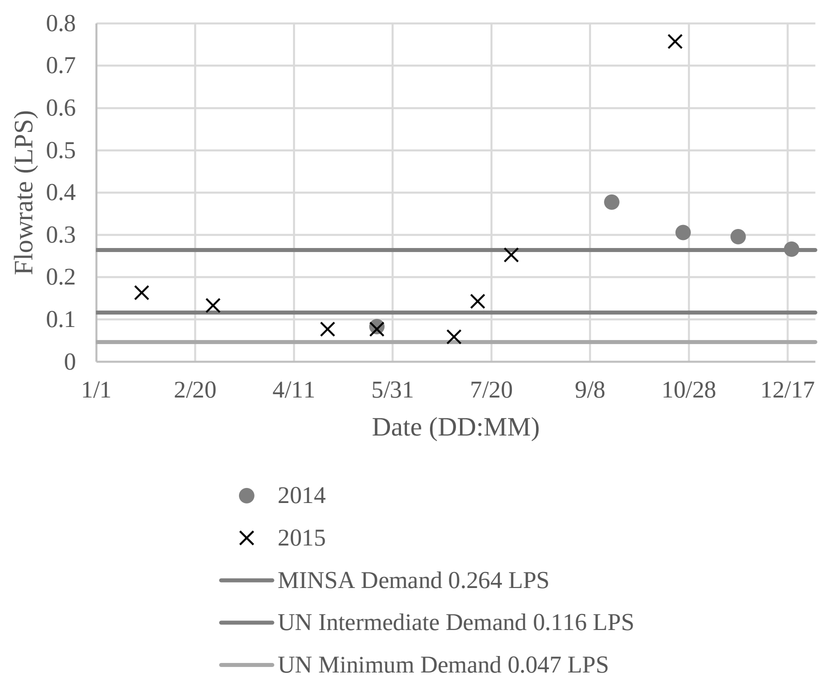

Figure 4.5. Flowrates Measured from April 2014 to October 2015.

It should be noted that flowrates increase and decrease seasonally, but can also increase or decrease significantly from day to day. There are often large storms, and also periods of drought, during the wet season that can affect flowrates. Also, collecting flowrates from an unprotected source is difficult. This is generally done by building a clay dam to direct spring flow into a measurement vessel. Often there is not impermeable clay available to build a dam, so leakage occurs when trying to direct water into the measurement vessel. A spring box was constructed in March, 2015 and was subsequently used to make flowrates measurements. Measurements made after construction of the spring box are expected to be more reliable than those made using the clay dam method. More measurements in subsequent years of operation would improve the usefulness of this graph.

4.3.7 Period of Operation

Knowing how the supply decreases over time and knowing the operation cycle is helpful in deciding how to create a demand pattern for IWS operation. Table 4.3 shows the available volume of water per capita for different periods of operation and at different supply rates. It was assumed that the tank fills from empty during the periods not in operation. These values were calculated using two methods. First, flowrates were calculated in LPCD for the family with the longest fill time required to reach their allotted volume of water. Second, Initial tank volumes were calculated in LPCD for the population of Espavé. The lower of the two results was the value used for the available volume. For example, for a supply of 0.077 LPS and an operating time of 1 hour and 15 minutes, Equation 4.4 shows the volume available at the tap is calculated as:

Equation 4.4

$$\frac{0.18\,LPS\ \times 1.25\,h \times 3600\,s}{22\,people} = 36.8\,LPCD$$

Where 0.18 LPS is the flowrate from the tap. The volume available from supply is calculated in Equation 4.5 as:

Equation 4.5

$$\frac{0.077\,LPS\ \times 24\,h \times 3600s}{201\,people} = 33.1\,LPCD$$

Therefore, the volume per capita is limited by supply at 33.1 LPCD.

As can be seen in Table 4.3, a period of operation that is too short limits available water at the outlet. This merely shifts water use to the next day, which is not feasible (or sustainable) if the goal is to manage water consistently on a day-to-day basis. For the SWMM analysis, it is most helpful to know the period of operation that will maximize water supply.

Table 4.3. Available Volume in LPCD for a Given Period of Operation and a given Supply. (Values in bold font indicate the earliest time at which the full daily supply is available)

Period of Operation (H:M)	Flowrate from Supply (LPS)							
	0.116	0.110	0.100	0.090	0.080	0.077	0.070	0.059
0:15	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
0:30	14.7	14.7	14.7	14.7	14.7	14.7	14.7	14.7
0:45	22.1	22.1	22.1	22.1	22.1	22.1	22.1	22.1
1:00	29.5	29.5	29.5	29.5	29.5	29.5	**30.1**	**25.3**
1:15	36.8	36.8	36.8	36.8	**34.4**	**33.1**	30.1	25.3
1:30	44.2	**47.3**	**43.0**	**38.7**	34.4	33.1	30.1	25.3
1:45	**50.0**	47.3	43.0	38.7	34.4	33.1	30.1	25.3
2:00	50.0	47.3	43.0	38.7	34.4	33.1	30.1	25.3
3:00	50.0	47.3	43.0	38.7	34.4	33.1	30.1	25.3
4:00	50.0	47.3	43.0	38.7	34.4	33.1	30.1	25.3

A period of operation that is too long limits refill time in the tank. However, longer refill times do not impact available volume per capita. At a flowrate of 0.90 LPS and an operation period of 1.5 hours, the volume available is 38.7 liters/capita. An operation period of 0.5 hours decreases the volume available to 14.7 liters/capita. It is assumed that a larger initial tank volume will be better, because it will give the system the best chance to reach full pressure, allowing shorter periods of operation to be more favorable.

Operation periods for simulation were chosen based on the highest volume of water per capita for supply flowrates of 0.116 LPS, 0.077 LPS, and 0.059 LPS and the shortest required operating period. Because the SWMM model only allows monthly, daily, and hourly patterns; the nearest hourly operation period was chosen. For example, at 0.077 LPS of inflow the shortest period of time to reach 30.1 LPCD is 1.25 hours, so the operation period of 1 hour was chosen. Initial tank volumes were input from the total volumes found for each period of operation and flowrate.

4.3.8 Demand

Patterns can also be created in SWMM as multipliers of the base inflow for each node. Because water is leaving the system, the base inflow at each outflow node is a negative value. For the SWMM model base demand was set to -0.0045 LPS at each node. For each situation, the pattern was chosen to be constant over the operating period with demand equal to the available volume of water in the tank. This was done by choosing an appropriate multiplier. Equation 4.6 shows how the multiplier is used to balance inflows and outflows in the system.

Equation 4.6

$$multiplier \times period\ of\ operation \times .0045\ LPS \times 1440\ s \times 27\ outlets = initial\ tank\ volume$$

Table 4.4 shows what the hourly multiplier should be for each given period of operation and supply flowrate. For a supply flowrate of 0.059 LPS, the optimal period of operation would be 1 hour and the multiplier 12.14 would be the input in the time pattern for each hour simulated. A 4-hour constant demand pattern was sufficient in all cases to allow all of the flows in the system to go to zero, indicating that the limited supply had been completely depleted.

Table 4.4. Hourly Multiplier for Given Period of Operation and Supply. (Values in bold font indicate the multiplier to be used in the simulation for the corresponding flowrate)

Period of Operation (H:M)	**Flowrate from Supply** (LPS)							
	0.116	0.110	0.100	0.090	0.080	0.077	0.070	0.059
1:00	14.14	14.14	14.14	14.14	14.14	**14.14**	14.44	**12.14**
2:00	**12.00**	11.35	10.32	9.28	8.25	7.94	7.22	6.07
3:00	8.00	7.57	6.88	6.19	5.50	5.29	4.81	4.05
4:00	6.00	5.67	5.16	4.64	4.13	3.97	3.61	3.03

Higher demand in the system was modeled by increasing the multiplier to 1000 for all scenarios. This multiplier was sufficiently high to allow outflow in the system at its maximum rate. The purpose of doing this was to look at how the system would operate if community members were using the maximum amount available to them at each tap. This observed behavior can be a result of perceived water scarcity in supply-limited systems.

4.3.9 Alternating Operation

Alternating the operation was considered as a possible solution to improving access to water during periods of IWS. This was simulated by dividing the model into two sections. Each section was then modeled independently of the other. This was only done for a supply flowrate of 0.77 LPS. Table 4.5 shows how household deliveries were staggered. The households in the upper elevations were given a longer tank refill time to account for water that would remain in the pipes.

Table 4.5. Alternating Operating Periods

	Period 1 Begins	**Period 2** Begins
12 hour stagger	Day 1 - 6 am	Day 1 - 6 pm
24 hour stagger	Day 1 - 11 am	Day 2 - 6 am
Household	P2, P3, P4, P5, P6, P7, P9, P10, P11, P31, P38, P39, P40	P8, P12, P14, P15, P16, P17, P18, P20, P22, P23, P25, P26, P29, P30, P32

4.3.10 Tank Relocation

Relocating the tank was also considered as a possible technical solution to decreasing inequality of access in the system. The tank was moved to a location at the north branch of the system and connected to node P3. Node P3 was then moved to a short branch off of the original node. The tank elevation was retained, and the connecting pipe lengths were estimated based on previous visits to the household because there is no existing survey data for this scenario.

4.3.11 Continuity Error

In order for the results to be useful, continuity error had to be managed and understood in the model. Equation 4.7 shows how SWMM calculates continuity error (Rossman, 2015). Continuity error can be reduced by shortening the routing time step. It can also be artificially decreased by making the initial storage extremely large. Using hourly demand variability for the model had the effect of yielding large negative continuity errors.

Equation 4.7

$$\left(1 - \frac{initial\ storage + total\ inflow}{final\ storage + total\ outflow}\right) \times 100\%$$

These large continuity errors, however, did not necessarily invalidate the results. Large negative inflows were used in the model to simulate demand. If these negative inflows had been calculated in Equation 4.7 as the outflows that they represent, continuity error would have been reported as a small positive number as opposed to a large negative number. In order to know if the results were useful it was necessary to look at the continuity error at each node. This approach also had the benefit of being able to see where the highest error occurred and understand what in the model was causing the error.

5 Results

Results show that EPANET is an effective tool for modeling CWS operation of a water distribution system. EPA SWMM was effective for IWS modeling, but difficult to work with. The best scenario for equality of service across the distribution network is to maintain CWS in the system. However, if this is not possible, SWMM can be used to model technical solutions for more equal distribution under IWS conditions.

5.1 Supply vs. Demand

First, it is necessary to look at supply vs. demand in this system. During the design of the Espavé system, it was recognized that during certain times of the year supply would not meet demand (Glenn, 2014). The measured flow rates in the system are shown in Table 5.1.

Table 5.1. Supply vs. Demand for UN Basic Access, Intermediate Access, and MINSA Recommendation.

Months Measured	Daily Available Flow (L)	Difference UN Basic (L)	Difference UN Intermediate (L)	Difference MINSA (L)
		4020	**10100**	**22800**
May 23, 2014	7170	3150	-2880	**-15700**
September 19, 2014	32600	28600	22600	9770
October 25, 2014	26400	22400	16400	3570
November 22, 2014	25500	21500	15500	2670
December 19, 2014	23000	19000	13000	174
January 24, 2015	14100	10100	4050	**-8730**
March 1, 2015	11400	7380	1350	**-11400**
April 28, 2015	6650	2630	**-3400**	**-16200**
May 23, 2015	6650	2630	**-3400**	**-16200**
July 1, 2015	5080	1060	**-4970**	**-17700**
July 13, 2015	12300	8280	2250	**-10500**
July 30, 2015	21800	17800	11800	**-1030**
October 21, 2015	65400	61400	55400	42600

As can be seen in the table, the flowrate from the source is able to meet the UN basic level of service of 20 LPCD throughout the year. At the basic level, water is only available for consumption and basic hygiene needs, and health risks remain high (Howard & Bartram, 2003). Water delivery at an intermediate level of service is more desirable because it leads to better health outcomes. This level of service is achievable in all but the driest months of the year. The level of service recommended by the Panamanian Ministry of Health is only achievable during the peak rainy season.

Although supply is adequate to meet demand at a minimal level of service, there is a high likelihood that during at least part of the year the system will revert to intermittent service. The intermediate level of service is the closest match to how the system is actually operated. During the late part of the dry season, when flow rates begin to drop below the actual demand, the system reverts to IWS conditions. The system is then run intermittently until there has been enough rain to replenish flowrates in the source. It is important to understand how the system is functioning under IWS conditions in order to offer suggestions on how to best manage the system when supply is limited.

It is worthwhile to mention that Jessica Glenn originally modeled the system in NeatWork, which is specifically designed for modeling gravity-fed systems. Her model would not be expected to return the same results as EPANET. Furthermore, the system was not constructed to the exact specifications of the design. For the main lines in the system, the trenching would have more closely followed the survey lines. However, community members were responsible for digging trenches and locating their taps on their own property, and may have made last minute changes. Also, some households were removed from the system because they did not participate in work days, and in one case a tap was added for a community member who showed extra initiative and dedication in the construction of the system. Actual measured flowrates can be found in Appendix C, Figure C.1.

5.2 EPANET Analysis

Modeling in EPANET shows that during the peak of the rainy season the system works as designed, to provide an acceptable level of service at each household in the system. The flow control discs do a good job at throttling the flow and lowering pressures at the outlets to create more equitable distribution in the system.

Figure 5.1 shows pressure drops that correlate with periods of high demand in the daily pattern. The exception in this example is node P15, which has a small pressure drop compared to the others. This tap has a short length of conduit from the 1.5-inch main to the outlet, so friction losses in the pipe are smaller. A smaller aperture size in the flow control disc would be a solution to bring it more in line with the other nodes, although it already has the smallest size used at a diameter of 3 mm.

According to the model results, there were some other cases where the flow control discs were inappropriately sized, as seen in Figure 5.2. At node P11, the pressure dropped below zero during the peak demand period. Removing the flow control disc at this node solves the problem. This is also recommended for P7 and P23 which also exhibit large pressure drops that affect their level of service. This solution was implemented in the actual system at P20 which had a flowrate of only 2.4 L/min before the flow reducing disc was removed. In EPANET, P20 had relatively high pressures compared to other nodes. The difference is likely due to the fact that the location of the tap was moved during construction, and does not imply a lack of reliability in the model.

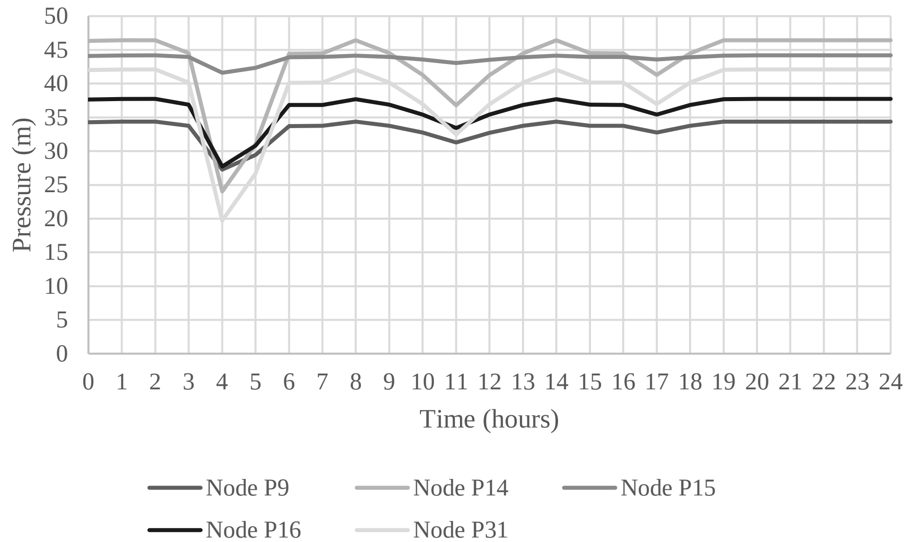

Figure 5.1. The Effect of Flow Reducing Discs on Node Pressures.

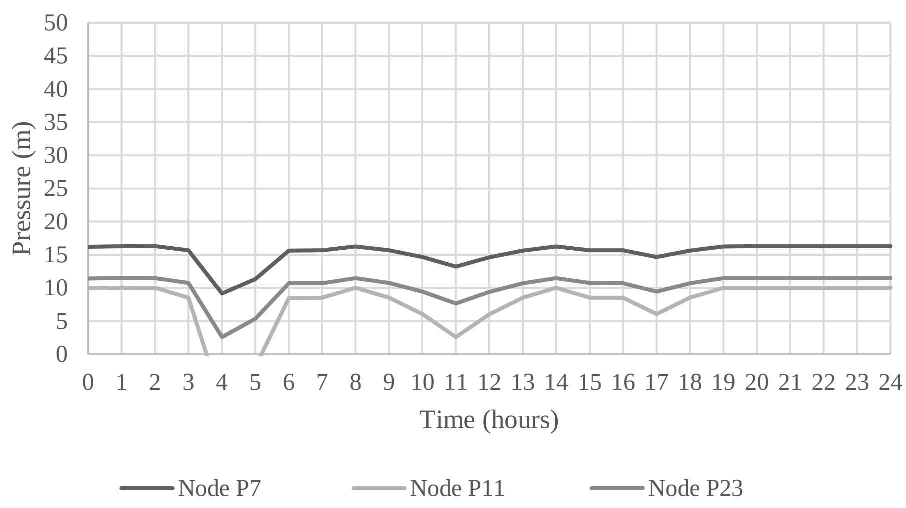

Figure 5.2. The Effect of Inappropriate Use of Flow Reducers, as Evidenced by Pressures Dropping below 10 m.

Because no pressure break tanks were used in the design of this system, households at low elevation have high pressures at the tap. At the same time, some of the high elevation households have very low pressures. This was addressed in the design by adding flow control discs before high pressure taps and using a large three-inch main leading to higher elevations. As a result, acceptable pressures range from four meters to 45 meters of head.

5.2.1 Supply

The model confirms that if supply meets demand, the water level in the tank will recover to its initial level over the course of a 24-hour period as seen in Figure 5.3.

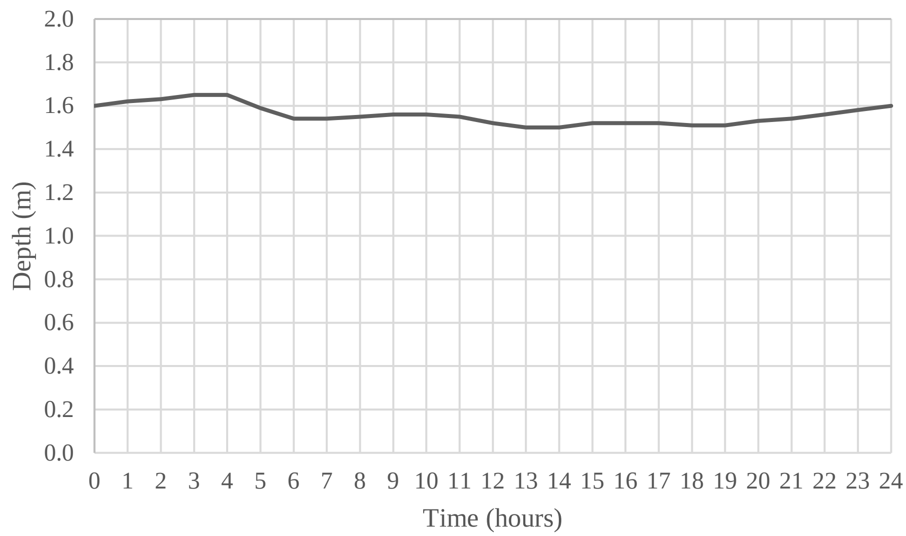

Figure 5.3. Tank Water Level Elevation (Supply of 6.98 L/min).

Figure 5.4 shows that, at the minimum flowrate, the water level drops 0.4 meters during the same period. This means that at the peak of the dry season, a full tank can supply the community for four days at 50 LPCD. A full tank is also sufficient to supply the MINSA-recommended 30 GPCD over a nine-hour period. At 20 LPCD, supply is still sufficient to meet demand.

At the peak of the dry season, it would take more than 4 days to refill the storage tank completely at a flowrate of 0.06 LPS. Although allowing the tank to completely refill would decrease the cycles of operation during IWS, it would also put the onus on the community members to store more water. This could lead to more opportunities for point-of-use contamination. On the other hand, more cycles would mean less water would need to be stored, but would create more wear and tear on the system. As a compromise, a 24-hour operation cycle offers daily access to clean water while avoiding much of the potential wear and tear on the system.

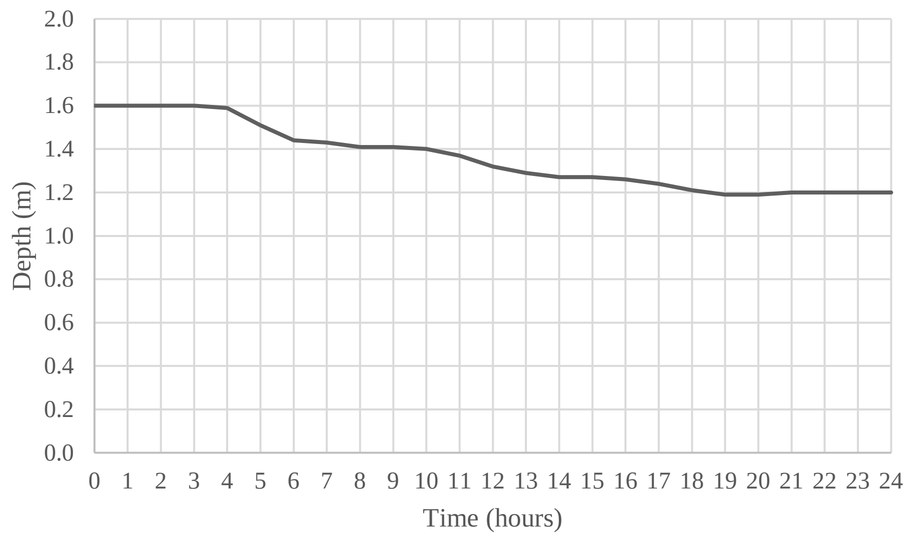

Figure 5.4. Tank Water Level Elevation (Supply of 3.53 L/min).

5.3 EPA SWMM Analysis

EPANET is limited to modeling systems under steady-state conditions, and thus; it is unable to model the non-steady-state conditions that occur when systems are operated intermittently. EPA SWMM is able to model IWS through the use of dynamic wave flow modeling, which uses the complete one dimensional St. Venant equations for momentum and continuity (Rossman, 2015). Therefore, modeling in SWMM is required in order to properly model the Espavé water distribution system when the water distribution system is not fully pressurized.

The three scenarios that were modeled in SWMM were the transition from continuous-to-intermittent supply, a measured mid-season supply, and the lowest measured supply for the dry season.

5.3.1 Tank Discharge

The transitional supply scenario assumes that supply to the tank is 50 LPCD, but that the system is being run intermittently. As can be seen in Figure 5.5, the tank will empty in about an hour when the model is set for a demand of 50 liters per capita over a two-hour period. At the inflection point of about 10 minutes, the system becomes pressurized and flow out of the tank decreases. This is because the pipes in the network are starting out empty and rapidly fill. Once the system is fully pressurized, it will function as modeled in EPANET for CWS.

At its maximum rate of demand, the system is never able to fully pressurize. This demonstrates what would happen in the system if all of the taps were allowed to flow freely at the same time. It is important to model this high demand rate because it is common for families to leave their taps open when supply is limited. Appendix D shows the results for how households are affected by IWS under both normal and high demand.

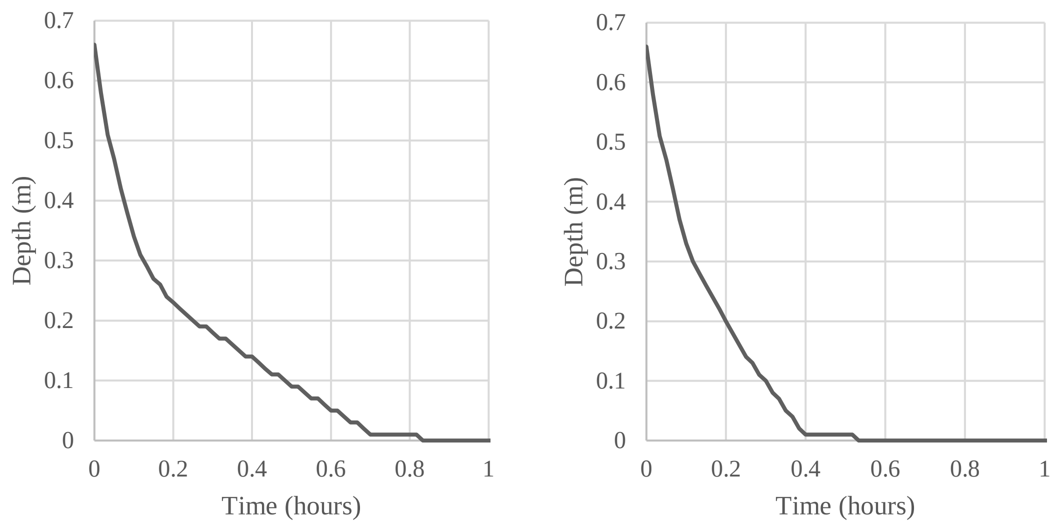

Figure 5.5. Time Difference between Tank Discharge when Demand Equals Supply (left) and Maximum Demand Possible from the System (right).

In the transitional supply scenario, the initial tank volume is 9,210, requring 22 hours to refill to that volume. It is possible to add up to another hour of refill time, as the entire volume discharges in less than an hour. However, the tank will not fully discharge if consumption is not high enough in the system. Allowing the tank to discharge for two hours allows ample time for the tank to discharge if consumption at the tap is too low to empty the tank in less than one hour.

For the mid-season and low supply scenarios, the volume of water stored in the tank is not sufficient to pressurize the entire distribution system. For the mid-season supply, it takes approximately 12 minutes for the tank to discharge completely, and for the low supply part of the season it takes less than 10 minutes.

5.3.2 System Pressurization

The transitional supply scenario is the only one in which the entire system reaches full pressure. While under full pressure the EPANET model applies. However, pressurization does not happen uniformly throughout the system. As can be seen in

Figure 5.6 the nodes along the spine of the system pressurize quickly within the first three minutes and the ones on the periphery of the system take the longest. It takes more than 20 minutes for P40 to pressurize.

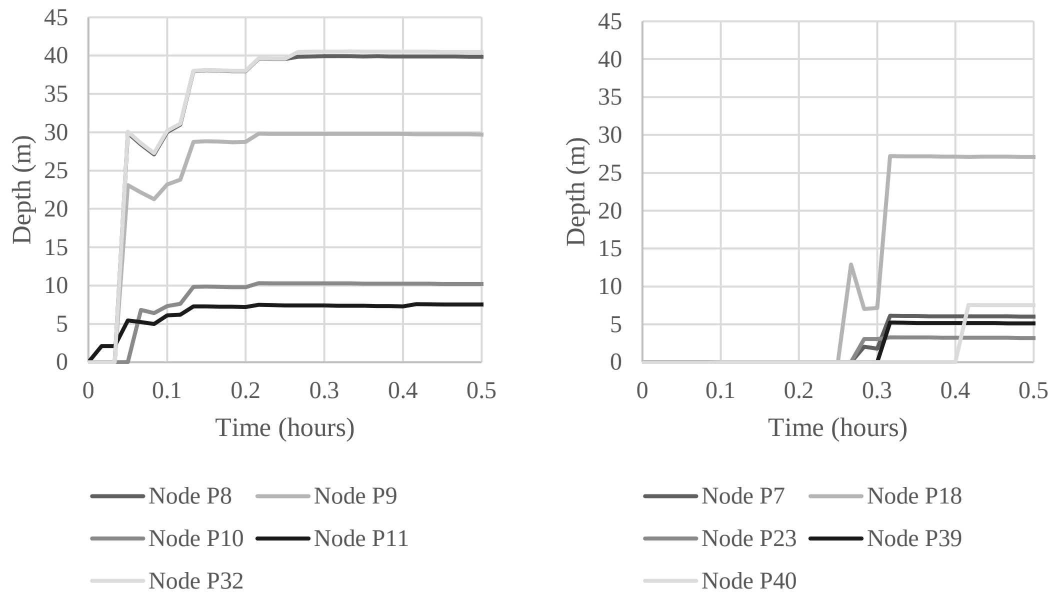

Figure 5.6.Time Difference between the First Households (left) and Last Households (right) to Receive Pressure.

In the mid-season and low supply scenarios, SWMM model results indicate that full pressurization of the system does not occur. Figure B.1 in Appendix B, shows the system map at the cresting point (the point at which the pipes in the system stop filling, and the total volume of water in the system begins to decrease) for the mid-season scenario with flow rates and head at the nodes. Flow is able to reach the high elevation end of the main on the far right side of the map, but the branching pipes at that location do not receive any flow. At the low elevation end, it can be seen that flow has reached the end of the system, but nodes have yet to be pressurized. After the cresting point, the main on the high elevation side of the system will reverse flow and the lower elevation will pressurize. This shortens the amount of time flow is available at full pressure at higher elevations, and increases the proportion of water available at the lower elevations of the system.

Figure 5.7 shows the proportion of households that are most affected by IWS operation of the distribution system. During the middle of the dry season, 55% of community members receive less than 20 LPCD. The number of highly effected households increases to 59% at the height of the dry season. Unlike conditions under the transitional supply scenario, elevation has a much greater effect than does proximity to the main line of the system. As the supply decreases, the advantage of households located at a lower elevation increases because they have more time with access to the available supply. Specific household flowrates, and access times can be found in Appendix D.

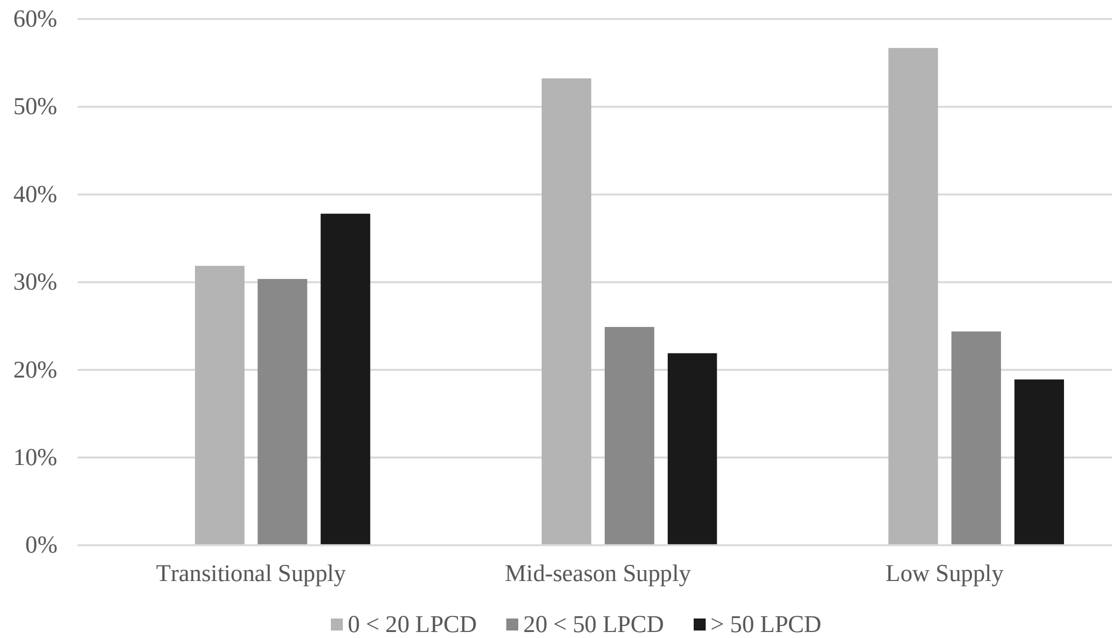

Figure 5.7. Distribution of Household Access due to IWS Operation (Demand=Supply).

5.3.3 Demand

Increasing demand in the system can also have negative effects. So far in the analysis it has been assumed that demand is equal to supply during the period in which the system is operating. By increasing the demand multiplier to be very high, it is possible to evaluate the system under more extreme conditions, allowing the water to flow out of the system as quickly as possible. This is meant to simulate all of the taps in the system open at once. Doing this causes the head at the taps to drop to zero, so looking at flowrate in the pipe just before the outlet is necessary.

Figure 5.8 shows flow in the pipes given a demand of 50 LPCD at each node. In this case the demand is spread out over a longer period of time and the flow is capped at that demand. The higher elevation links P3, P7, and P23 have a shorter period of time to meet demand than the lower elevation links P8 and P26.

Figure 5.9 shows the system running at its full hydraulic capacity. Higher demand in the system shortens the time water is available at each node. At node P23 there is no flow available to the pipe, and at nodes P7 and P3 time that water is available drops to under 0.5 hours. At P8 the drop in time that water is available is not as dramatic; however, the increase in flowrate increases the overall volume available at that location.

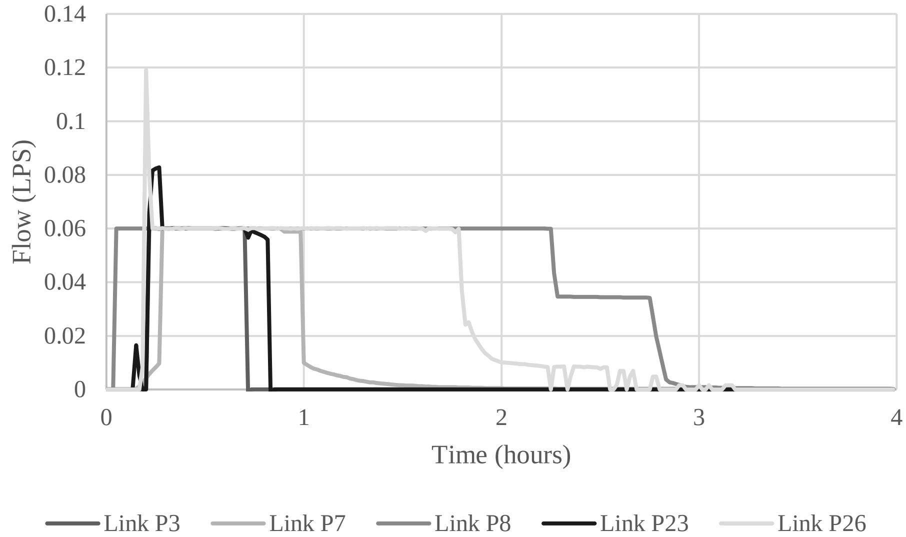

Figure 5.8. Representative Sampling of Modeled Flowrates from Outflow Pipes at 50 LPCD Demand.

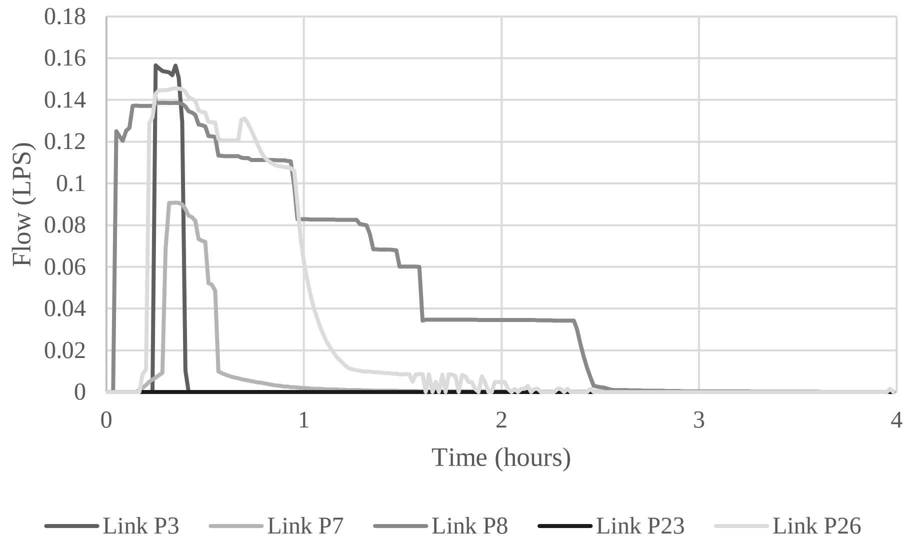

Figure 5.9. Representative Sampling of Modeled Flowrates from Outflow Pipes at High Demand.

Figure 5.10 shows how the system is affected by maximum demand at each node. In the case of transitional supply, the proportion of community members affected largely increases from lower levels of demand represented in Figure 5.7 above. Some of the households affected receive high flow rates for very short periods of time. Other households receive longer sustained flow, but at very low flowrates. Overall, 42% of community members do not have access to at least 20 LPCD in this scenario. In the mid-season supply scenario, the access to water actually increases under maximum demand. Under maximum demand, 53% of community members do not have access to at least 20 LPCD, while under average demand 55% do not have that level of access. In the low supply scenario, the percentage of people with minimum access to water does not change.

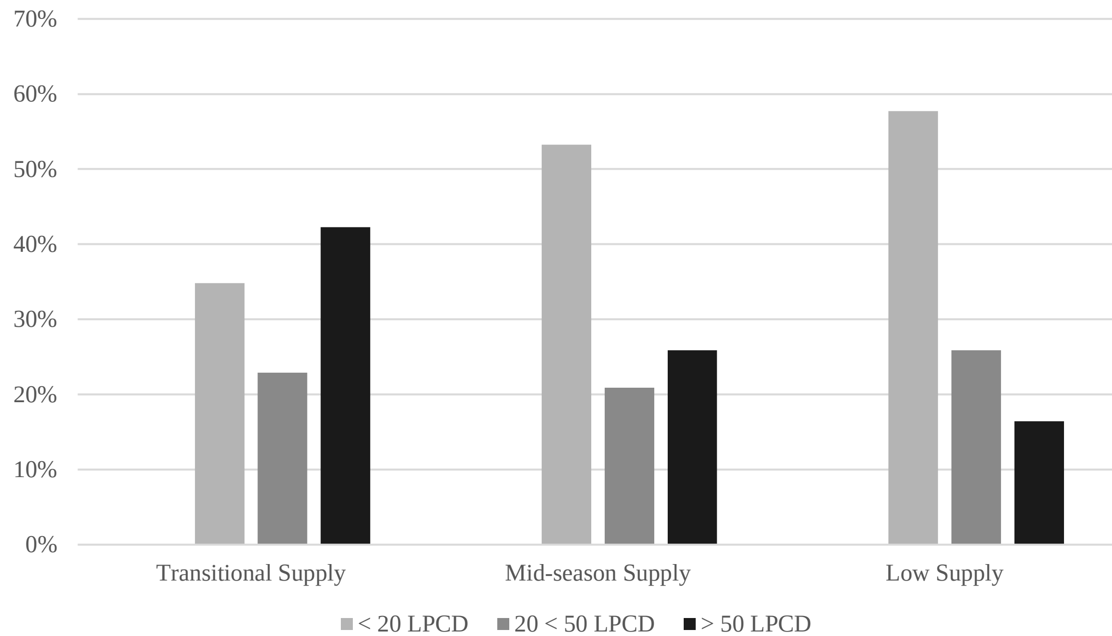

Figure 5.10. Distribution of Household Access due to Maximum Possible Demand.

In most cases, households that do not receive at least 50 LPCD receive even less under the maximum demand scenarios. Those households located closer to the spine of the system, however, seem to do better. Nodes P9 and P11 both show increases in water availability under every scenario when maximum demand is applied to the system.

5.3.4 Alternating Delivery and Tank Relocation

Model results indicate that alternating water deliveries would be helpful in improving equality among the households for the mid-season supply scenario, but that tank location would reduce access to most households. Figure 5.11 shows the results of two different staggering schemes and tank relocation.

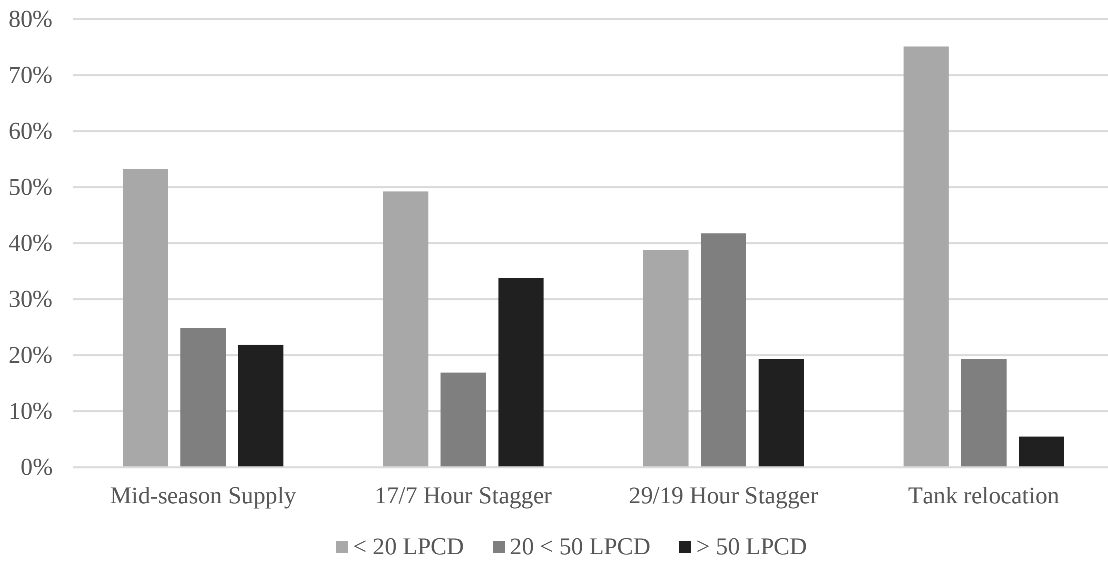

Figure 5.11. Effect of Alternating Delivery and Tank Relocation on Household Access.

Access is slightly improved when operation is staggered over two periods in the same day. In this scenario, households with access less than 20 LPCD decrease slightly from 53% to 49%. Staggering operation over two days does an even better job of improving access reducing the proportion of households with access to less than 20 LPCD to 39%. Furthermore, the number of household that receive in excess of 50 LPCD is decreased. This shows that water is being more fairly distributed in the system. In the two-day scenario, each household receives a minimum of 9.2 LPCD, whereas in all other mid-season supply scenarios there are households that do not receive any water delivery

Relocation of the tank has the effect of distributing access more evenly, but reducing access for 75% of families to less than 20 LPCD. In this scenario the number of households that receive zero access is decreased. Therefore, although access distributed more evenly at the lower levels, for most households it is not sufficient to meet 20 LPCD. In this particular case moving the tank would add extra associated costs at both the design phase, and post construction. Extending the transmission line to the new location would cost an additional $1.32 per foot. The cost of the tank for the system was $2,250 representing 28% of materials cost for the entire system (Glenn, 2014).

5.3.5 Continuity Errors and Instability

Table 5.2 shows the continuity errors and link instabilities for the three scenarios under the average demand case. The flow routing continuity errors reflect the high demand at the nodes over the course of the simulation run. A mass balance of the inflows and outflows in the system was done, and the continuity error was found to be at a much lower and more acceptable range.

Table 5.2. Continuity Errors for Average flow Scenarios.

	Transitional Supply	Mid-season Supply	Low Supply
Flow Routing	-163.9%	-313.8	-349.5%
Mass Balance	4.59%	5.41%	3.37%
Node		**Continuity Error**	
N9	12.24%	16%	19.23%
N22	-	-	1.74%
N61	2.71%	20%	-48.77%
N65	-2.41%	-3.77%	-5.42%
N81	-8.46%	58%	-
N85	1.88%	5.70%	-8.18%
Link		**Instabilities**	
104	1	1	2

Continuity errors at the nodes were usually found to be highest at nodes downstream of an orifice link followed by a conduit with an upward slope. This was the case for N61, N65, N81, and N85. It is likely that the error at these nodes was a result of backflow through the orifices as the system lost pressure

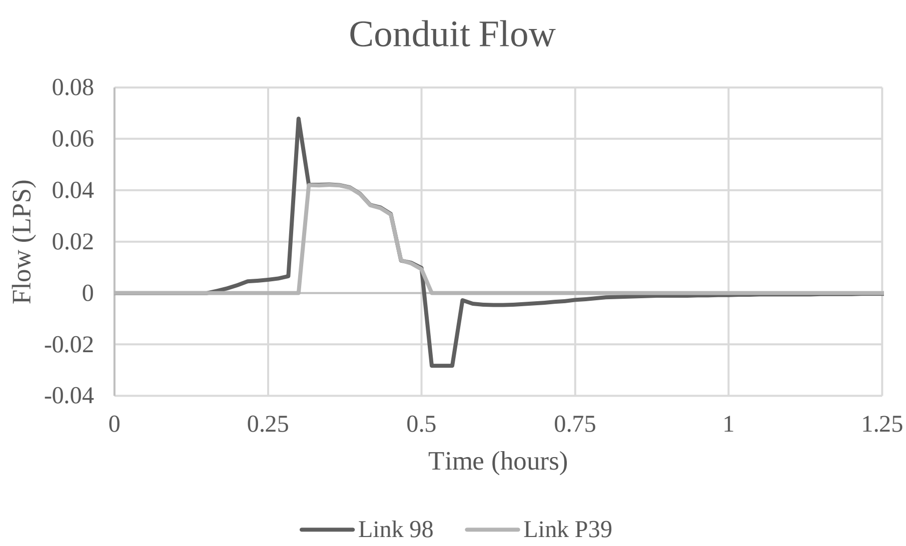

Figure 5.12. Flows through Conduit and Orifice attached to N81, Resulting in a Continuity Error.

. Figure 5.12 shows the flows for the conduit and the orifice attached to N81. As the system loses, pressure at about 0.5 hours, flow through the conduit goes to zero, while the orifice (Link 98) shows a brief period of negative flow, reflecting backwards flow of water into the main line. The conduit (Link P39) should also have negative flow at this point, as the stored water in the conduit drains back into the preceding link.

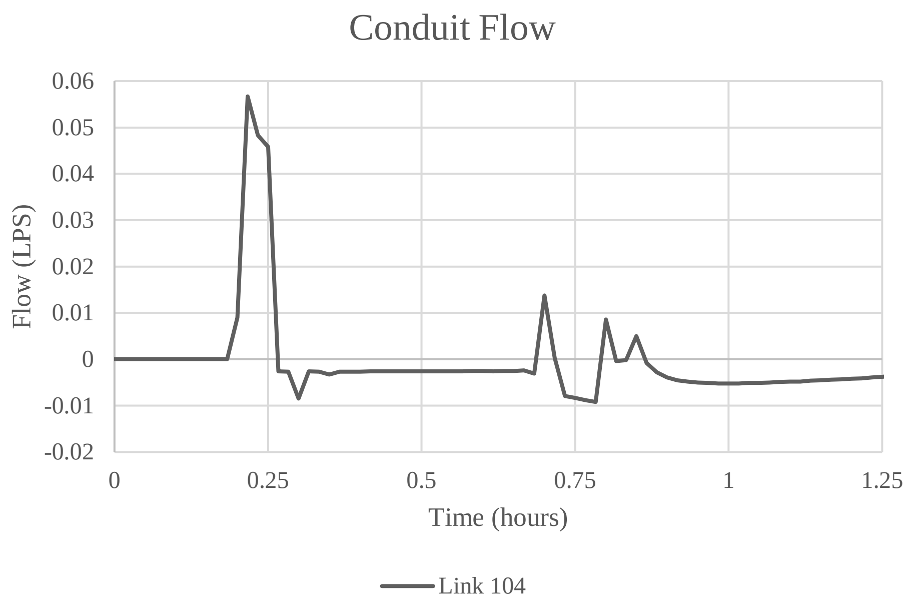

Figure 5.13. Flow Instability at Link 104.

Figure 5.13 shows that instabilities found in orifice link 104 could be related to the continuity error in the nodes. Like the orifice link 98, it is attached to a node with high continuity error, and that node is followed by a conduit with a positive slope. By decreasing the reporting time in the model, it is possible to get a better look at the instability occurring at 0.75 hours of elapsed time. This instability could be due to the receding flow in the main conduit as it passes below the link.

The only other major source of continuity error in the model was at N9. This was the node centrally located at the junction of all of the main branches of the system. The likely cause of the high continuity error at this node was an accumulation of error caused by the orifice nodes along the main lines of the system. Another possible contributing factor could be the reductions of pipe size at that node for two branches of the system.

6 Recommendations

A key observation that remains consistent throughout the analysis of the Espavé system is that the behavior of its users is the most important indicator of how it will perform. Scarcity driven water use behaviors can cause water distribution systems to revert to IWS when users deplete the total volume of water available from both the tank and distribution lines. This not only causes degradation of the pipes and fittings in the system, but it also drives inequality in how the water is distributed. This can be seen in the results of the SWMM analysis, with users closer to the main line and at lower elevations having increased access. Management and water use behavior, therefore, need to be addressed in any possible solutions to user inequality.

6.1 Avoiding IWS

The most obvious solution to maintaining equality in system wide delivery is to avoid IWS operation of the system. Gravity-fed water distribution systems are designed for continuous operation, and work best under full pressure. When designing a system it is important to work with the community, and educate them in the operation and management of the system.

One possible way to do this would be to work with community members to create incentives for water conservation during low supply periods. Most importantly, community members must understand that water must be left in the distribution system for it to function correctly, and that using every last drop at the tap causes inequality for their neighbors. There are several indicators that can help identify low supply in the system.

- **Tank Overflow -** The tank overflow can be monitored as flowrates are reduced in the dry season. When overflow from the tank disappears, over a period of two days or more, it is an indication that supply is falling below demand in the system.
- **Decreased Flowrates -** Decreased flow at the tap is a sign that water has dropped below the level of the tank and that the distribution system is being drained. If flowrates drop noticeably, use should be discontinued or rationed.
- **Indicator Households -** If a household loses service, this can be a sign to other community members that they need to reduce their household water use. In the case of Espavé, P23 would be a good indicator household, as they would be the first to lose access to flow in the system.

Monitoring the flowrate into the tank can also be helpful in managing water use in the system. Once the operator notices one of the low supply indicators, community members could be notified of water use restrictions based on the flowrate at the tank or the source. This could be done by posting the number of available buckets at community stores and churches and by word of mouth. Enforcement of these restrictions would be based on community-appropriate incentives or penalties, and depend on widespread knowledge of water availability.

In Panamá, a common storage vessel is a 5-gallon bucket. For Espavé this could be used as the baseline for a measurement system. Table 6.1 shows how many five gallon buckets would be available for use and storage each day for a given flowrate into the storage tank. The flowrate is given in how many seconds it takes to fill a 5-gallon bucket at the storage tank. A 20-second fill time is equivalent to 0.05 LPS or 21.5 LPCD for the community of Espavé

Table 6.1. Five Gallon Buckets Available per Household Based on Time to Fill One at Bucket the Tank.

	Llenado de un Tanque de 5 Galones del Fuente de Agua/ Time to fill a 5 gallon tank from the water source												
Tiempo/Time (segundos/ seconds)	20	17	16	14	13	12	11	10	9	8	7	6	5
Tanques/Tanks (5 Galones/ 5 Gallons)	8	9	10	11	12	13	14	16	17	19	22	25	30
	Tanques de Agua por Casa para Almacenamiento y Uso/ Tanks of water per house for storage and use												

Table 6.1 is specific to the community of Espavé, but it could be adapted to other communities by changing the household size and population. For simplicity and fairness, each household is allotted the same amount of water, but the community could agree to allocate water according to household size, especially if community members are paying different rates. In order for this system to work, a tap would have to be installed in the transmission line right before it reaches the tank. It would be necessary to include a valve to cut off flow to the tank, for an accurate measurement. It would also be recommended to include and equally sized valve and outlet for the tap and tank.

These educational tools should be used in future training for communities that are in the process of building a water distribution system, as well as communities that need help with the management and maintenance of existing systems. IWS is not currently mentioned in training manuals produced by the Peace Corps in Panama (Befus et al., 2015), and addressing this common situation could lead to improvements in communities that are struggling with inequality.

6.2 Alternating Delivery

Sometimes it takes just a few selfish or unaware members of a community to drive a system into IWS operation. The household at P23 has a very high incentive to conserve water, because they will be the first to lose service. There are other households, however, that are not as inconvenienced during periods of intermittent supply.

The SWMM model shows that alternating delivery in the system over a 2 day period can increase equality in system wide water delivery. Isolating the higher elevation portion of the distribution system allowed water to reach the higher elevation households for sufficient time to provide at least some flow at those outlets.

A successful strategy in staggering water delivery would have to incorporate training an operator to open and close appropriate valves on a daily basis. Alternating operation as a stand-alone strategy likely would not improve health outcomes in comparison to normal IWS operation because the contamination vectors such as leaks and household storage would still exist.

Alternating delivery still suffers from the problems of IWS operation. Lack of pressurization in the system can lead to pipe bursts. This is due to pressure spikes that occur when system is turned on. Pipe bursts could further lead to contamination from leaks. In the branched networks, however, pressure spikes from turning on the system would only occur every other day. This is an improvement over normal IWS operation. Two-day staggering would mean that deliveries would only occur every other day at each household. It would be necessary to train community members to properly store water and to monitor for leaks in the system to help improve hygiene during IWS operation.

6.3 Usefulness

As a design tool, SWMM is much more limited in its usefulness than EPANET. EPANET was designed specifically for modeling water distribution systems, is easier to work with, and can model chemical concentration, water age and tracers. Furthermore, systems should not be designed for intermittent operation. Other drawbacks to working with SWMM were that it was time intensive, and many of the inputs had to be manipulated to match the EPANET model. Further, there were significant continuity errors and instabilities that had to be understood and reduced as much as possible in order to validate the results.

Given these drawbacks, SWMM is still a useful tool for analysis. Modeling the Espavé system in SWMM provided a better overall picture of how the system operates during IWS. Using statistical information from the model on average flow rate, it was possible to determine which households would be most affected by both IWS and high demand for the different supply scenarios. The SWMM model also offered a method for analyzing the effects of alternating deliveries in two sub-sections in the system.

6.4 Future Work

This report has been mostly focused on the mechanisms that cause IWS, and how water distribution systems can be modeled to improve access. The water quality aspect of operating a small gravity-fed system under IWS conditions, was not addressed. In the future water samples from the households in Espavé could be analyzed to find out if there is a correlation between IWS and contaminants in the system. This could be combined with a survey of community members to understand their perceptions of level of service, health, and other factors that relate to the operation of the system and how it affects their lives.

7 Conclusion

IWS is a problem that is only expected to increase in the coming years as water systems that were installed during the years of the Millennium Development Goals come of age. In Panamá, increasing population in rural areas is driving up demand for fresh water, while in recent years drought has reduced supply. Because of climate change, it is also possible that the dry seasons will become more pronounced in the future.

There are many reasons to avoid operating water distribution networks under IWS conditions. IWS reinforces scarcity water behaviors such as over-withdrawal and storage. Negative pressures in the network can lead to damaged and leaky pipes as well as poor health outcomes due to contamination in damaged pipes or point of use contamination of stored water. Furthermore, operation under IWS conditions has been shown to exacerbate inequality in distribution network water delivery.

Working with communities on proper water use behavior is likely the best solution to the problem of low supply. In order to maintain CWS in a gravity-fed distribution network it is important to educate community members on the importance of maintaining water pressure in the distribution lines. NGO's that work with communities on gravity-fed water systems should focus more time on training for the operation and maintenance, organization, leadership, and financial management aspects of these systems.

In the case that CWS cannot be maintained, modeling the system can help to understand how a water distribution network will behave under IWS conditions. EPANET can be used to model the system and understand how it should function under CWS conditions. Knowing pressure and flow characteristics can help to improve service under those conditions. EPA SWMM can then be used to model the system under IWS conditions. Dynamic wave flow routing allows modeling of non-steady-state flows, and can identify the households that will be most impacted by IWS. It can further be used to improve equality in water distribution by strategically alternating the deliveries to different parts of the system. Although EPANET is designed for modeling water distribution systems, it cannot model non-steady-state flows; and while SWMM can model non-steady-state flows, it is not meant for modeling water distribution systems, and lacks many of the features in EPANET that would make it more useful and easier to work with. Therefore, public-domain software specifically designed for modeling IWS in water distributions systems is needed to improve results and usability.

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Appendix A. Copyright documentation

Map of Panamá by Google Maps. Obtained from https://www.google.com/maps/@8.2548769,-80.0291637,8z?hl=en. Unlicensed permission under fair use as described in Section 107 of the US Copyright Act and Google Maps Terms of Service. Accessed 2017.

Map of Espavé. Obtained from Google Earth. Unlicensed permission under fair use as described in Section 107 of the US Copyright Act and Google Earth Terms of Service. Accessed 2017.

Appendix B. EPA SWMM Schematic of Espavé

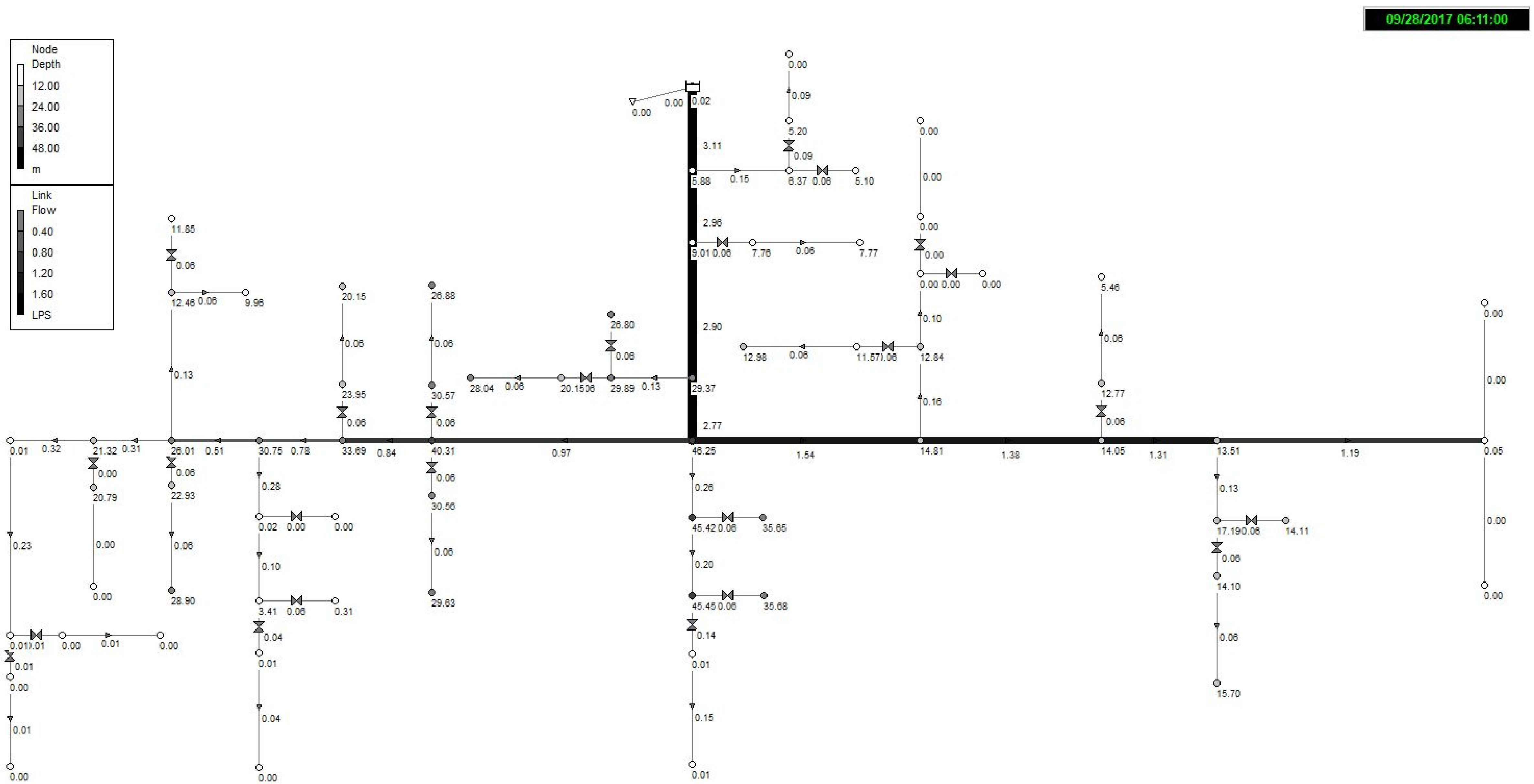

Figure B.1. EPA SWMM Schematic Showing the Point at which Water Stops Flowing into the System from the Tank and Upper Elevation Flows begin to Reverse

Appendix C. Measured Flowrates

Table C.1. Measured Flowrates for the Community if Espavé.

Pluma	Time (s)	Flowrate (L/s)	Flowrate (L/m)	Flowrate (L/h)	Flowrate (GPM)
P2	5.71	0.18	10.5	630	2.77
P3	-	-	-	-	-
P4	6.63	0.15	9.0	540	2.39
P5	-	-	-	-	-
P6	4.74	0.21	12.6	756	3.34
P7	5.08	0.20	12.0	720	3.12
P8	-	-	-	-	-
P9	4.76	0.21	12.6	756	3.33
P10	-	-	-	-	-
P11	5.65	0.18	10.8	648	2.8
P12	4.86	0.21	12.6	756	3.26
P14	11.30	0.09	5.4	324	1.4
P15	-	-	-	-	-
P16	-	-	-	-	-
P17	14.00	0.07	4.2	252	1.13
P18	14.60	0.07	4.2	252	1.08
P20	25.70	0.04	2.4	144	0.62
P22	4.88	0.20	12.0	720	3.25
P23	7.83	0.13	7.8	468	2.02
P25	4.11	0.24	14.4	864	3.85
	8.43	0.12	7.2	432	1.88
P26	13.90	0.07	4.2	252	1.14
P29	4.41	0.23	13.8	828	3.59
P30	-	-	-	-	-
P31	5.13	0.19	11.4	684	3.09
P32	-	-	-	-	-
P38	-	-	-		
P39	5.68	0.18	10.6	634	2.79
P40	5.11	0.20	11.7	705	3.1

Appendix D. EPA SWMM Results

Table D.2. Household Access during Transitional Supply Period due to IWS.

Transitional Supply – Initial Tank Volume = 10050 L					
Link	**Household Size**	**Time of Access** (H)	**Flowrate** (LPS)	**Total Access** (L)	**Individual Access** (LPCD)
P2	3	0.5	0.060	108	36.0
P3	12	0.5	0.060	108	9.0
P4	8	3.9	0.017	239	29.8
P5	4	1.4	0.054	272	68.0
P38	7	0.8	0.062	179	25.5
P6	5	1.5	0.049	265	52.9
P7	20	3.8	0.012	164	8.2
P39	6	0.7	0.052	131	21.8
P40	4	3.0	0.033	356	89.1
P10	2	2.0	0.030	216	108.0
P11	22	4.0	0.019	274	12.4
P8	8	4.0	0.039	562	70.2
P32	4	4.0	0.040	576	144.0
P12	10	3.9	0.053	744	74.4
P9	9	4.0	0.028	406	45.1
P31	9	2.5	0.049	441	49.0
P14	9	2.2	0.059	467	51.9
P15	3	2.2	0.058	459	153.0
P16	6	2.0	0.056	403	67.2
P17	1	3.9	0.026	365	365.0
P18	1	2.6	0.051	477	477.0
P20	2	3.9	0.034	477	239.0
P22	14	3.4	0.026	318	22.7
P23	10	0.7	0.059	149	14.9
P25	5	3.0	0.038	410	82.1
P26	6	3.0	0.041	443	73.8
P29	5	0.9	0.063	204	40.8
P30	6	2.0	0.052	374	62.4
		Total Volume (L)		9588.3	
	Continuity Error =	(1 – 9588.3/10050) x 100		4.59%	
		Average Time (H)		2.5	

Table D.3. Household Access during Mid-season Supply Period due to IWS.

Mid-Season Supply - Initial Tank Volume = 6646 L					
Link	**Household Size**	**Time of Access** (H)	**Flowrate** (LPS)	**Total Access** (L)	**Individual Access** (LPCD)
P2	3	0.0	0.000	0	0.0
P3	12	0.0	0.000	0	0.0
P4	8	3.9	0.009	126	15.8
P5	4	0.8	0.049	141	35.3
P38	7	0.2	0.070	50	7.2
P6	5	0.9	0.037	120	24.0
P7	20	3.8	0.003	41	2.1
P39	6	0.0	0.033	0	0.0
P40	4	3.0	0.023	248	62.1
P10	2	2.0	0.012	86	43.2
P11	22	4.0	0.013	187	8.5
P8	8	4.0	0.033	475	59.4
P32	4	4.0	0.035	504	126.0
P12	10	3.7	0.047	626	62.6
P9	9	4.0	0.021	302	33.6
P31	9	2.4	0.040	346	38.4
P14	9	1.6	0.062	357	39.7
P15	3	1.6	0.059	340	113.0
P16	6	1.3	0.056	262	43.7
P17	1	3.9	0.017	239	239.0
P18	1	2.0	0.048	346	346.0
P20	2	3.9	0.026	365	183.0
P22	14	2.8	0.020	202	14.4
P23	10	0.0	0.049	0	0.0
P25	5	2.3	0.036	298	59.6
P26	6	2.4	0.035	302	50.4
P29	5	0.3	0.073	79	15.8
P30	6	1.3	0.052	243	40.6
		Total Volume (L)		6286.7	
	Continuity Error =	(1 – 6286.7/6646) x 100		5.41%	
		Average Time (H)		2.1	

Table D.4. Household Access during Low Supply Period due to IWS.

Low Supply – Initial Tank Volume = 5082 L					
Link	**Household Size**	**Time of Access** (H)	**Flowrate** (LPS)	**Total Access** (L)	**Individual Access** (LPCD)
P2	3	0.0	0.000	0	0.0
P3	12	0.0	0.000	0	0.0
P4	8	3.9	0.004	56	7.0
P5	4	0.6	0.038	82	20.5
P38	7	0.0	0.000	0	0.0
P6	5	0.6	0.016	35	6.9
P7	20	0.0	0.000	0	0.0
P39	6	0.0	0.000	0	0.0
P40	4	3.0	0.019	205	51.3
P10	2	2.0	0.005	36	18.0
P11	22	4.0	0.011	158	7.2
P8	8	4.0	0.028	403	50.4
P32	4	4.0	0.031	446	112.0
P12	10	3.7	0.041	546	54.6
P9	9	4.0	0.017	245	27.2
P31	9	2.5	0.033	297	33.0
P14	9	1.5	0.054	292	32.4
P15	3	1.5	0.052	281	93.6
P16	6	1.2	0.049	212	35.3
P17	1	3.9	0.013	183	183.0
P18	1	1.9	0.043	294	294.0
P20	2	3.9	0.021	295	147.0
P22	14	2.6	0.014	131	9.4
P23	10	0.0	0.000	0	0.0
P25	5	2.8	0.028	282	56.4
P26	6	2.2	0.028	222	37.0
P29	5	0.2	0.028	20	4.0
P30	6	1.2	0.044	190	31.7
		Total Volume (L)		4910.8	
	Continuity Error =	(1 – 4910.8/5082) x 100		3.37%	
		Average Time (H)		2.0	

Table D.5. Household Access during Transitional Period due to High Demand.

Transitional Supply – Initial Tank Volume = 10050 L					
Link	**Household Size**	**Time of Access** (H)	**Flowrate** (LPS)	**Total Access** (L)	**Individual Access** (LPCD)
P2	3	0.2	0.102	73	24.5
P3	12	0.2	0.137	99	8.2
P4	8	3.9	0.019	267	33.3
P5	4	0.9	0.082	266	66.4
P38	7	0.4	0.125	180	25.7
P6	5	1.0	0.093	335	67.0
P7	20	3.8	0.006	82	4.1
P39	6	0.2	0.032	23	3.8
P40	4	3.0	0.027	292	72.9
P10	2	2.0	0.038	274	137.0
P11	22	4.0	0.024	346	15.7
P8	8	4.0	0.048	691	86.4
P32	4	4.0	0.050	720	180.0
P12	10	3.8	0.060	821	82.1
P9	9	4.0	0.043	619	68.8
P31	9	2.3	0.052	431	47.8
P14	9	1.5	0.089	481	53.4
P15	3	1.5	0.083	448	149.0
P16	6	1.3	0.075	351	58.5
P17	1	3.9	0.018	253	253.0
P18	1	1.9	0.041	280	280.0
P20	2	3.9	0.032	449	225.0
P22	14	2.8	0.030	302	21.6
P23	10	0.0	0.000	0	0.0
P25	5	3.2	0.055	634	127.0
P26	6	3.8	0.058	793	132.0
P29	5	0.4	0.090	130	25.9
P30	6	1.3	0.109	510	85.0
		Total Volume (L)		10148.4	
	Continuity Error =	(1 – 10148.4/10050) x 100		-0.98%	
		Average Time (H)		2.3	

Table D.6. Household Access during Mid-season Supply Period due to High Demand.

Mid-Season Supply - Initial Tank Volume = 6646 L					
Link	**Household Size**	**Time of Access** (H)	**Flowrate** (LPS)	**Total Access** (L)	**Individual Access** (LPCD)
P2	3	0	0.000	0	0.0
P3	12	0.0	0.000	0	0.0
P4	8	3.9	0.009	126	15.8
P5	4	0.6	0.056	121	30.2
P38	7	0.1	0.105	38	5.4
P6	5	0.7	0.059	149	29.7
P7	20	3.8	0.001	14	0.7
P39	6	0.0	0.000	0	0.0
P40	4	3.0	0.021	227	56.7
P10	2	2.0	0.016	115	57.6
P11	22	4.0	0.015	216	9.8
P8	8	4.0	0.040	576	72.0
P32	4	4.0	0.042	605	151.0
P12	10	3.7	0.054	719	71.9
P9	9	4.0	0.031	446	49.6
P31	9	2.4	0.038	328	36.5
P14	9	1.2	0.082	354	39.4
P15	3	1.2	0.075	324	108.0
P16	6	1.0	0.066	238	39.6
P17	1	3.9	0.011	154	154.0
P18	1	1.6	0.036	207	207.0
P20	2	3.9	0.024	337	168.0
P22	14	2.5	0.014	126	9.0
P23	10	0.0	0.000	0	0.0
P25	5	3.0	0.038	410	82.1
P26	6	2.0	0.042	302	50.4
P29	5	0.2	0.062	45	8.9
P30	6	1.0	0.088	317	52.8
		Total Volume (L)		6495.1	
	Continuity Error =	(1 – 6495.1/6646) x 100		2.27%	
		Average Time (H)		2.1	

Table D.7. Household Access during Low Supply Period due to High Demand.

Low Supply – Initial Tank Volume = 5082 L					
Link	**Household Size**	**Time of Access** (H)	**Flowrate** (LPS)	**Total Access** (L)	**Individual Access** (LPCD)
P2	3	0.0	0.000	0	0.0
P3	12	0.0	0.000	0	0.0
P4	8	3.9	0.004	56	7.0
P5	4	0.5	0.033	59	14.9
P38	7	0.0	0.000	0	0.0
P6	5	0.4	0.006	9	1.7
P7	20	0.0	0.000	0	0.0
P39	6	0.0	0.000	0	0.0
P40	4	3.0	0.019	205	51.3
P10	2	2.0	0.007	50	25.2
P11	22	4.0	0.012	173	7.9
P8	8	4.0	0.035	504	63.0
P32	4	4.0	0.038	547	137.0
P12	10	3.5	0.051	643	64.3
P9	9	4.0	0.024	346	38.4
P31	9	2.4	0.028	242	26.9
P14	9	1.1	0.077	305	33.9
P15	3	1.1	0.070	277	92.4
P16	6	0.8	0.060	173	28.8
P17	1	3.9	0.008	112	112.0
P18	1	1.4	0.037	186	186.0
P20	2	3.9	0.020	281	140.0
P22	14	2.4	0.005	43	3.1
P23	10	0.0	0.000	0	0.0
P25	5	1.8	0.034	220	44.1
P26	6	1.8	0.033	214	35.6
P29	5	0.0	0.000	0	0.0
P30	6	0.8	0.077	222	37.0
		Total Volume (L)		4867.6	
	Continuity Error =	(1 – 4867.6/5082) x 100		4.22%	
		Average Time (H)		1.8	