Hydraulic Modeling and Water Distribution Optimization in Corregimiento Kuna Nega, Panama City, Panama

Interactive Qualifying Project Report completed in partial fulfillment of the Bachelor of Science Degree at Worcester Polytechnic Institute

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Abstract

In Corregimiento Kuna Nega, Panamanians do not have a reliable source of potable water – a constitutionally-protected human right. We worked with IDAAN, the government water authority, to develop a hydraulic model of Kuna Nega's current water network to optimize distribution and increase access. To build our model, we gathered data on flow rate, pressure, elevation, among other variables, in the field. We designed a more efficient water delivery schedule, providing enhanced service to users for longer periods. Finally, we provided recommendations on additional infrastructure to extend service to more residents.

Acknowledgements

The successful completion of this Interactive Qualifying Project would not have been possible without the outstanding guidance and advice from our advisors, sponsors, and mentors. We would like to thank the following people for their support and encouragement.

- Valmy Guerrero, our sponsor from Footprint Possibilities Inc. who helped to advise the group from August through October;
- Rick Montanari, a former sponsor from Footprint Possibilities Inc. who advised the group during the months leading up to our arrival in Panama;
- Kevin Batista, the head engineer of Distribution and Loss Control at IDAAN, who worked closely with us to outline our project goals and expectations;
- Javier Sanchez, the IDAAN head engineer of Optimizations at the Water Treatment Plant in Chilibre, who offered a great deal of knowledge regarding the delivery process from extraction, to purification, to distribution;
- Juan Li, an electromechanical engineer at IDAAN, who offered vital information regarding pump schematics required to generate the system model;
- Enrique Ortega, an engineer with 35 years of experience with IDAAN, who helped us determine the specifications of the pipelines;
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- The many other engineers and workers at IDAAN who provided us with transportation in the field and with the necessary tools to gather our data;
- Gray Hauff, a former group member who helped in the preliminary stages of the project in research, writing, and organization.

Executive Summary

Purpose and Goal

The focus of our work was collecting data from field research to analyze and optimize the distribution of potable water in a district on the outskirts of Panama City, Panama. Our case study has been experiencing an extreme water shortage due to a rapidly growing population, deteriorating infrastructure, and imbalanced distribution. The area studied ranged from the Chivo Chivo Pump Station in Panamá, Panama, to its downstream district of Corregimiento Kuna Nega which encompasses the neighborhoods of Santa Librada Rural, Villa Cardenas, El Valle de San Francisco, Kuna Nega, and Genesis. Residents in this area are supplied with potable water between once and three times per week in the wet and dry season, respectively. Considering the population in Panama currently has a growth rate of 1.3% per year, the funds allocated to the maintenance of water infrastructure is not nearly high enough. More than half of the water supplied to the greater metropolitan area of Panama City is not paid for by consumers or directly compensated by the national government, and this loss directly affects the national water authority's (IDAAN) ability to provide water.

Our goal for this project was to collaborate with the engineers in IDAAN's Optimization Department to generate a hydraulic model of the district using EPANET software and the information we gathered in the field to recommend a rotational delivery schedule that would maximize water distribution in an equitable manner. As an extra deliverable, our sponsor requested that we audit their design plans for constructing a pipeline between the Patacón Pump Station and a new pump station in Santa Librada Rural which would, in theory, provide enough water to the region to offset the current deficiencies. Table ES.1 outlines the work plan IDAAN provided for us:

Objective	Deadline
Update ArcGIS internal mapping system	9/5/22 - 9/9/22
Count homes in the district to determine total demand	9/5/22 - 9/9/22
Measure flow rates and pressure values at different points in the system	9/12/22 - 9/16/22
Analyze Patacón design plan	9/19/22 - 9/23/22
Generate EPANET model	9/26/22 - 9/30/22
Revise EPANET model	10/3/22 - 10/6/22

Table ES.1 IDAAN's work plan for us to follow, with deadlines.

Methods

For at least three days each week, our team met with the engineers at IDAAN's office to touch base on the project's progress, determine which data remained to be gathered, and then go into the field and to learn and plot the current distribution system. We took pressure and flow rate measurements at key pipeline junctions, tanks, and pump stations in the system which established a baseline to compare our simulations. We also collected the required information for the simulation software, including pipe dimensions and specifications, node elevations, and start/end points of different lines and pump systems. To gain an accurate idea of the demands of the community, we used Google Earth to estimate the population of the community. We then processed the data into a value of water demand in gallons per minute at each node in the hydraulic model. During our time in the field, we also took the opportunity to get first-hand accounts from members of the community about the state of the system and the effects it has on the residents. These data points were taken into account when comparing the current delivery schedule as it appears in sponsor documents to the lived reality of residents. To add another dimension to our project, we spoke with engineers at the Chilibre Water Treatment Plant to gain insight into the water treatment process and the mechanics of clean water provision that ensures the health and well-being of the community.

Deliverables

Based on the data gathered, we generated four deliverables and several visual aids that we submitted to IDAAN:

1. ArcGIS Model Update: IDAAN uses the ArcGIS software as their company’s internal means of tracking the growth of their hydraulic systems. Because the population has been growing so rapidly, IDAAN’s current records have fallen behind in documenting their current infrastructure and the engineers have not updated the maps of areas like Corregimiento Kuna Nega since 2014. We updated the maps to reflect their current state, documenting pipes, junctions, and material specifications as seen in Figure ES.1, so the information in our simulation models would match IDAAN’s records.

Figure ES.1. ArcGIS model of existing hydraulic pipelines. Blue lines reflect pipes that existed in the model already, and red lines reflect pipes that we added.

2. House Count and Demand Values: To update IDAAN's population estimates, we counted the number of houses in the area using Google Earth's satellite view. We conducted a census of visible roofs by subsection of the water delivery network. We took these frequencies and calculated error terms to provide IDAAN with new total demand flow at each node in our model. This way, we could tell if our simulation met the demand and whether or not we needed to alter our system configuration.

3. EPANET Model: Our core tool in evaluating the efficacy of our methods was also one of our main deliverables. IDAAN asked us to submit our EPANET model, as seen in Figure ES.2, to determine an optimized water delivery schedule. In the event that a water shortage develops again, they could revisit our model and create a new optimized schedule. They can also use the basis of our work to

generate models for other regions that are experiencing similar problems to Corregimiento Kuna Nega.

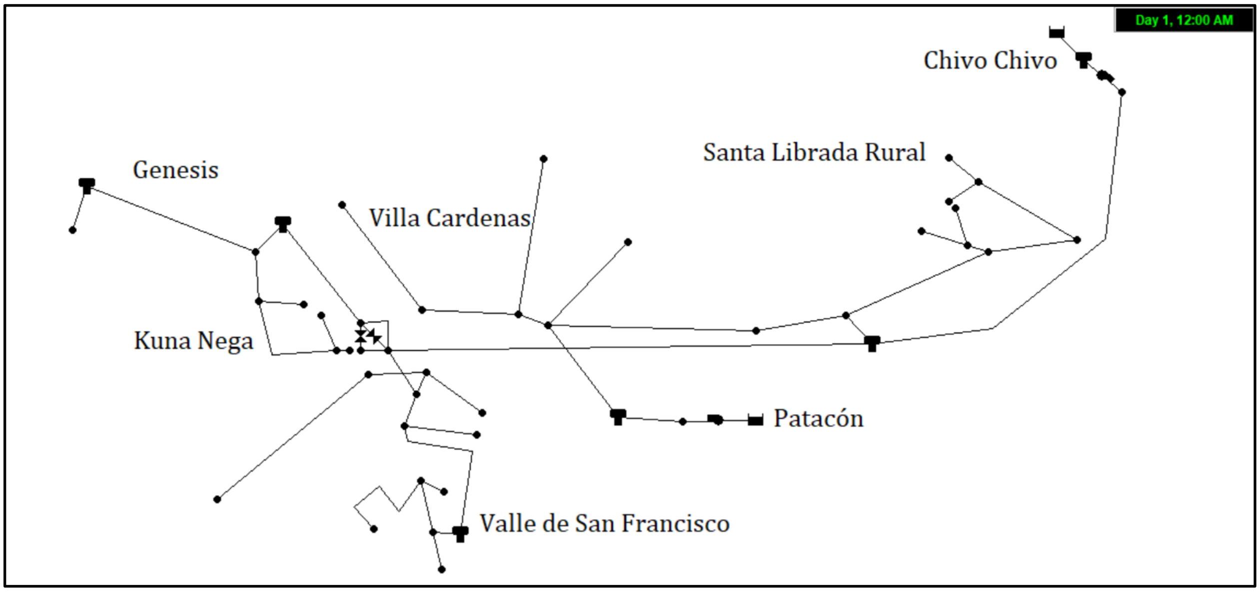

Figure ES.2. The final model of the hydraulic water delivery system in Corregimiento Kuna Nega which was used to generate the proposed water delivery schedule.

4. Proposed Water Delivery Schedule: Based on the simulations we ran on our EPANET model and our conclusions on the equitability of the distribution, we generated a schedule for water to be delivered to each neighborhood. (Table ES.2).

Junction	Monday							Tuesday							Wednesday						
	8:00	10:00	12:00	14:00	16:00	18:00	NITE	8:00	10:00	12:00	14:00	16:00	18:00	NITE	8:00	10:00	12:00	14:00	16:00	18:00	NITE
Santa Librada				🟩	🟩	🟩	🟩														
Villa Cardenas 1	🟩	🟩	🟩																		
Villa Cardenas 2								🟩	🟩	🟩	🟩	🟩	🟩								
Villa Cardenas 3								🟩	🟩	🟩	🟩	🟩	🟩								
Valle de SF 1				🟩	🟩	🟩	🟩														
Valle de SF 2				🟩	🟩	🟩	🟩														
Valle de SF 3														🟩	🟩	🟩	🟩				
Valle de SF 4														🟩	🟩	🟩	🟩				
Valle de SF 5														🟩	🟩	🟩	🟩				

Junction	Thursday							Friday							Saturday							Sunday						
	8:00	10:00	12:00	14:00	16:00	18:00	NITE	8:00	10:00	12:00	14:00	16:00	18:00	NITE	8:00	10:00	12:00	14:00	16:00	18:00	NITE	8:00	10:00	12:00	14:00	16:00	18:00	NITE
Santa Librada				🟩	🟩	🟩	🟩																					
Villa Cardenas 1	🟩	🟩	🟩																									🟩
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Villa Cardenas 3								🟩	🟩	🟩	🟩	🟩	🟩									🟩	🟩	🟩	🟩	🟩	🟩	
Valle de SF 1				🟩	🟩	🟩	🟩																					
Valle de SF 2				🟩	🟩	🟩	🟩																					
Valle de SF 3														🟩	🟩	🟩	🟩											
Valle de SF 4														🟩	🟩	🟩	🟩											
Valle de SF 5														🟩	🟩	🟩	🟩											

Table ES.2. The proposed water delivery schedule, broken down by region of Corregimiento Kuna Nega.

Conclusions

With the optimized water delivery schedule, we hope to increase water availability to Corregimiento Kuna Nega while ensuring that each neighborhood receives equal amounts of water based on population distribution. We also made varied recommendations based on the model. For example, we recommend an investigation into the Santa Librada Rural that behaves differently in our simulated model than the recorded data. We also recommend increasing the diameter of pipes in North Villa Cardenas. We hope our work has proved useful to IDAAN, and that we have improved water access in Corregimiento Kuna Nega. Water scarcity is not an inconvenience for Panamanians. This lack of access to water affects daily life and places the people's health and dignity at stake.

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Chapter I: Introduction

1.1 The Problem: Water Scarcity

During Panama's wet season, thunderstorms spawn from skies that were clear an hour before. The torrent is carried away by thick gutters that line streets and walkways. People shelter under any overhang to wait out the downpour. The reservoirs are full, but on most days, the taps are dry. Even in one of the rainiest countries on earth, water is piped to the neighborhood of Kuna Nega only two times a week.

In Panama's most recent amendment to the Constitution (2004), Article 188 states that "The State has the fundamental obligation to guarantee that its population lives in a healthy environment, free of contamination (pollution), and where air, water, and foodstuffs satisfy the requirements for proper development of human life" (Panama's Constitution of 1972 with Amendments through 2004, 2014). Yet, the current water system in many communities in Panama underserves residents and underperforms the state's constitutional obligations. Poor water pressure and flow issues present challenges in water distribution, and the government incompletely addresses old and failing infrastructure, such as leaky pipes and broken pump stations. Many politicians in the Kuna Nega area campaign on the promise to install new infrastructure to expand access to potable water. Although these politicians often do fulfill their promises, long-term solutions like maintenance, a crucial component of sustainable water distribution, are not implemented. Funds are limited and investing in new projects to better serve a community is futile if the existing infrastructure cannot be adequately maintained.

When the power frequently goes out in the Chilibre, the metropolitan region's largest water treatment plant, residents are cut off from their water supply without notice (CE Financial News English - CENFENG, 2022). Approximately 97% of people who live in affluent areas have access to water, while only 80% of people in impoverished areas do. Furthermore, in some indigenous populations, access to potable water reaches as low as 35% of the population, which further aggravates conditions of poverty ("Voluntary National Review," 2020, p.101). For many Panamanians living in rural and depressed neighborhoods outside the city, a steady supply of potable water is not guaranteed. This lack of access to water creates great inequalities in these communities and rising tensions among classes who can and cannot afford to live in areas with access to water. Beyond economic inequalities, the unsteady supply of water for the people of Kuna Nega leads to poor health outcomes, premature deaths, and a diminished quality of life. Water is a central part of life: necessary for sanitation, domestic chores, and, of course, drinking. The people's health and dignity are at stake.

1.2 The Solution: Hydraulic Model Optimization

To solve water scarcity issues, we developed a hydraulic model. A hydraulic model uses mathematical equations to calculate and visually represent factors such as flow, velocity, pressure, and water level in a water system network. We used EPANET, a computer program developed by the United States Environmental Protection Agency, to evaluate the Chivo Chivo Pump Station and the neighborhood it supplies, Corregimieto Kuna Nega. After building the model, we evaluated a plan to add a new pipeline to the region.

Our project aids the current situation by developing a hydraulic model optimization (HMO) that addresses the water distribution issues within the system, focusing on the five neighborhoods in the periphery of the capital that constitute Corregimiento Kuna Nega. With the help of our sponsor, IDAAN (Instituto de Acueductos y Alcantarillados Nacionales), the national authority for water and wastewater projects, we gathered the information needed to create our model.

We began by collecting data. Going into the field to verify measurements, we tracked changes to the infrastructure so we could update their online system diagrams, and gained insight into the lives of the communities where IDAAN provides service. We then built the hydraulic model. We modeled multiple rotation schemes and compared them on the basis of how much water could be supplied to each region under different system configurations. Values including output flow and output pressure were the main variables used to evaluate these configurations. We then evaluated the system's response to changes in pressure and flow conditions to make further refinements. We used the model to determine which scenarios provided optimal pressure at all nodes and supported consumption by users at established rates. We sent the results of our model to IDAAN. Finally, we proposed a series of recommendations based on the results that included changes to pipework, changes to valve settings, and additional studies that can be performed.

Our optimized water distribution plan recommends a water delivery schedule to each section of a neighborhood based on a variety of factors like water supply and demand, topography, and time of day, among other variables. Our study outlines a clear timetable for neighborhood water supply to ensure that water flow in the pipes remains adequate. IDAAN engineers can apply this plan to other communities facing similar issues. We designed the HMO with the communities' consumption patterns in mind. Each pocket of a neighborhood has different consumption habits, so communicating with the affected community is crucial to developing a model that properly addresses the needs of the people and ensures efficient access to a life-sustaining resource. Over the course of the past seven weeks, have worked to secure a reliable water schedule for the more than 11,000 residents of Corregimiento Kuna Nega.

Chapter II: Literature Review

2.1 Section Overview

This chapter provides an overview of IDAAN, outlining their principal responsibilities to the Panamanian people as a government agency, and the tools they use to implement proper sanitization and water distribution practices. We summarize the general approaches taken and common schools of thought about the stakeholders in Panama's water system to tackle the issue of supplying clean water to Panamanians. Finally, we outline the water system modeling software, EPANET, and highlight its key features.

2.2 Water Infrastructure in Panama

After a long period of colonization, Panama separated from Colombia in 1903, becoming a sovereign nation. Just days later, the United States and Panamanian governments signed the Hay-Bunau-Varilla Treaty, giving the US authority to build and control the Panama Canal. The construction of the Canal precipitated the modernization of the city's potable water distribution and sanitization systems and the construction of the Colón and Panama aqueducts. Large reservoirs of fresh water were created in Gatún, Miraflores, and Alajuela to feed the operations of the Canal – where each trip through the locks require some 52 million gallons of water (*Lago Alajuela, Panama*, 2010). These reservoirs contain about 1.5 trillion gallons of water in total among the three of them (Lewis & Beard, 1972).

After the reservoirs, the first aqueduct was finished and began service on July 4th, 1905, in Panama City. A decade later, in 1914 and 1920, aqueducts began branching out of the city. These aqueducts were constructed in the cities of Aguadulce, Pesé, and Las Tablas, all of which were privately owned by Americans. It was not until 1942 that the United States government gave Panama control over the distribution network, pump stations, and valves located in Panama and Colón. The United States government controlled the water treatment plant, Miraflores de Mount Hope, until the year 1953 (*Historia – IDAAN WEB*, 2021).

On November 28th, 1956, the Panamanian government created the Commission of Aqueducts and Sewers of Panama (CAAP) for the study, design, and construction of the aqueduct system of the city of Panama, representing the first government agency not under direct US control. The government later renamed CAAP to IDAAN. On January 1st, 1956, work started to execute better aqueducts and sewer systems in the city of Panama.

In 1972, the Miraflores water plant could no longer supply enough water for the capital city, so the Panamanian government began the construction of an additional water plant, Chilibre, which is located right at the intersection between the Chagres River and Lake Alajuela on the border of the Panama-Colon Provinces. On October 10th, 1975, this new facility was finished and is now the major supplier of potable water to the country, producing 125 million gallons of water daily. According to the engineers at IDAAN (J. Sanchez, personal communication, September 5, 2022), Chilibre currently provides approximately 90% of Panama City's supply with the remaining 10% provided by the Miraflores and Caboras treatment plants, as well as some nearby wells.

Understanding how the current water distribution and water treatment systems in Panama work together to deliver water to houses is an essential part of our project. Figure 2.1 depicts this process.

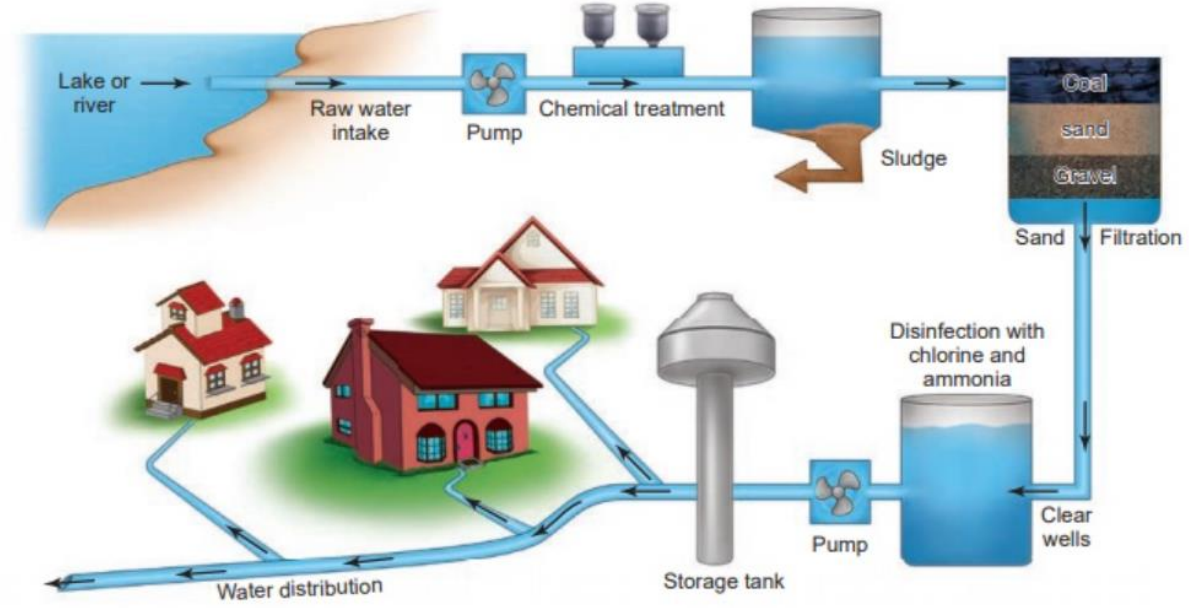


Figure 2.1. The basic steps of the water delivery system, showing how water is drawn from its source, treated for consumption, stored, and eventually brought to homes ("The Water Distribution and Water Treatment System," n.d.).

In the past, IDAAN has taken a reactive approach, geared towards dealing with emergencies as they occurred. In recent years, the organization has been more focused on fixing water systems before they fall into disrepair, shifting from a reactive to a proactive mindset. Historically, collecting fees for water has been difficult, and IDAAN has struggled to take on all the projects without proper financial support. The city of Colón implemented a performance-based contract in 2018 to improve the dire state that the water system was in, which resulted in improvements for the city such as steady water supply, increased volume of water, more expansive coverage, and better payment collections (*Utilizing Performance-Based Contracts to Enhance Public Services Delivery: A New Approach to Water Provision in Colón, Panama*, 2018). The performance-based contract was key to the success of this project. Since work to construct, repair, and improve upon the Colón facilities was paid for in installments, and final payments were withheld until approved by an independent engineering agency, the contractors were invested in the project's success.

2.3 IDAAN's Current Water Treatment Practices

The water distributed by IDAAN undergoes heavy treatment prior to distribution. The agency is required by law to follow the rules outlined in the most recent 2021 COPANIT (Panamanian Commission on Technical and Industrial Rules) document. This document details the physical, inorganic, and organic chemical tests that must be performed as well as tests to determine radioactive and biological characteristics in drinking water (Titulo II de La Ley 23, 2019). Physical tests are completed by observing factors like turbidity (clarity), PH, and smell. Inorganic tests determine the presence of harmful inorganic chemicals like lead, while organic tests check for pesticides and detergents. Radioactivity in drinking water is defined by its levels of radon. One example of a biological characteristic of drinking water is the amount of fecal bacteria present. Since drinking water can become contaminated in many ways, IDAAN often follows industry regulations provided by the Environmental Protection Agency (EPA) and the American Water Works Association (AWWA).

As previously mentioned, the vast majority of the water treatment is done at Chilibre. At this station, water is withdrawn from the lake by four large hydraulic pumps and is sent over a half a mile to the station where it undergoes a series of processes to produce clean drinking water that is delivered to the greater metropolitan area by aqueducts or tank trucks (Figure 2.2).

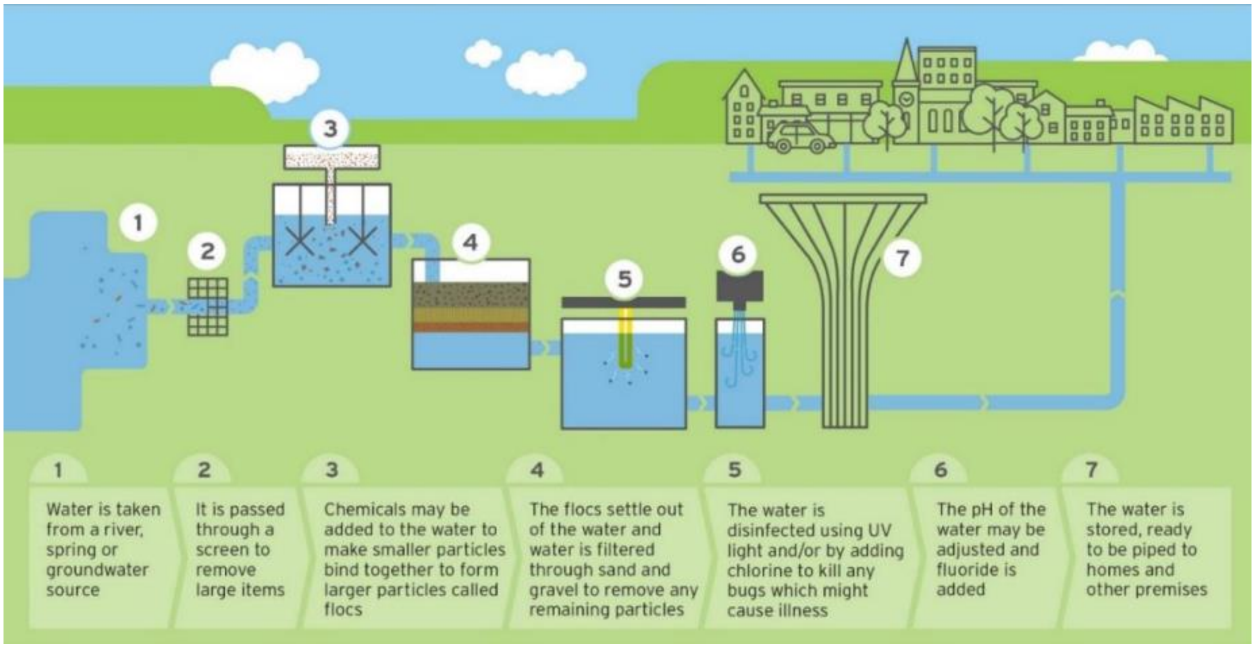


Figure 2.2. The basic process of water treatment, explaining the steps that are followed to ensure clean drinking water ("How We Clean Our Water to Make It Safe to Drink," 2018).

First, the water is mixed with chlorine and alum powder, the common name for potassium aluminum sulfate, and ionized polymers to disinfect the water and generate flocs within the water (Figures 2.3, 2.4). Flocs are congregations of particles that would otherwise cause the water to have a high turbidity. The water circulates through a winding system of channels where sanitation and flocculation occur. Along the way, dead algae rise to the top of the water and form a thin layer of film which is periodically skimmed off. Once the flocs have sedimented to the bottom of the system, the water passes through a sand mixture to filter the few remaining flocs out. From here, the water flows to the two covered holding tanks which store 5 million gallons of potable water each, and which are pumped into the city or driven to remote areas in tank trucks (J. Sanchez, personal communication, September 5, 2022).

Figures 2.3-2.4. Water, piped from the reservoir, which is being mixed with chlorine and alum powder in the preliminary treatment steps. Chlorine is delivered through the labeled white PVC piping (left) and the water lines and Alum Powder storage tanks (right).

Every two hours, scientists test the water on-site by looking for microbes that make drinking the water unsafe. IDAAN’s labs use microscopes designed to look for these specific microbes and periodically run ELISA protocols (protein and enzyme detection kits) and Colilert kits (E. Coli and coliform bacteria detection kits) on individual channels to more easily identify when and where the process is failing. Currently, there are no systems in place to detect and remove microplastics or per- and polyfluoroalkyl substances (PFAS), which are harmful chemicals when ingested, but it is a problem that the engineers at the treatment facility aim to combat in the near future (J. Sanchez, personal communication, September 5, 2022).

2.4 Problems Currently Facing IDAAN

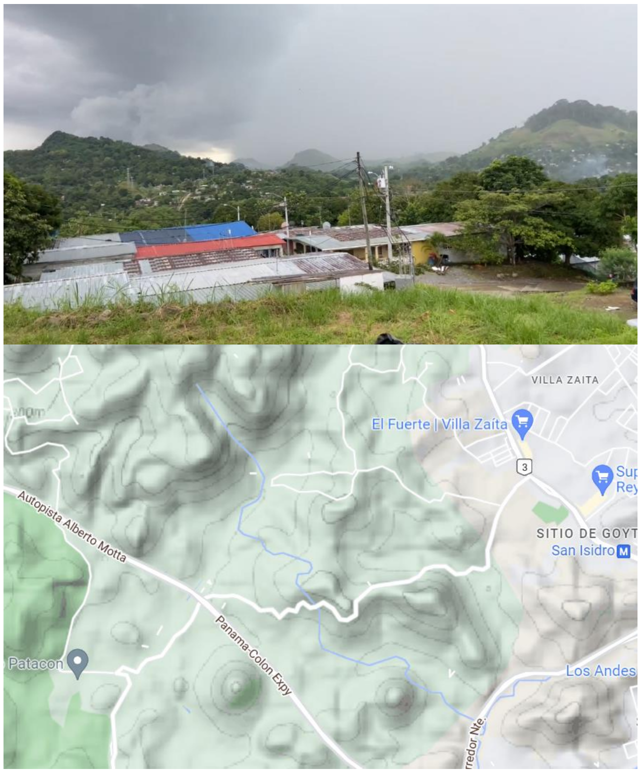
Since its foundation in 1961, IDAAN has faced many challenges in getting clean water to all residents. IDAAN’s principal challenge involves water leakage and shrinkage since these variables make it difficult to optimize the networks and schedule water distribution. Leaks are often caused by an increased amount of high pressure in the early mornings when usage is low. Although these leaks are usually small, they often go unnoticed for long periods of time and the amount of water loss accumulates, resulting in significant aggregate water loss. As seen in

Figures 2.5-2.7, these leaks can occur in any region of the network: at the pipes transporting the water, pumps, or storage tanks.

Figures 2.5-2.7. Examples of three leaks observed in the field: at Santa Librada Rural (left), at pump #1 in the Chivo Chivo pump station that services the Lucha Franco region just north of Santa Librada (middle), and a valve in Kuna Nega (right).

Shrinkage, a form of theft, is the result of unauthorized water connections to the network. IDAAN currently estimates about 55% of the water that leaves the treatment plants for distribution throughout the city is not paid for by the populace. Shrinkage directly hits IDAAN's financials, making it difficult to invest in routine maintenance or the expansion of services. According to our contacts at IDAAN, the vast majority of people living in Corregimiento Kuna Nega do not pay for their water. IDAAN reports that this pattern is true in most poor neighborhoods throughout the country. In contrast, the payment rate remains high in affluent areas such as the city. Although water fees are calculated at a standard rate and are easy to pay online, at banks, and local grocery stores, a large number of residents still do not or cannot pay. Through IDAAN, we requested information about the demographics of our case study from the Kuna Nega town hall. We requested information about median income, the literacy rate, who makes up the population (indigenous peoples, immigrants, etc). However, the last Census occurred over 10 years ago because the COVID-19 pandemic delayed the 2020 Census. That said, the general population of Kuna Nega tends to be low-income with higher levels of indigenous and afro-Panamanians who, historically, have had less access to government assistance and other opportunities as compared to their whiter counterparts. As a result, it is common to voluntarily default on payments to IDAAN and redirect their money to feed their families and clothe their children. With an informal understanding that those who cannot pay will not be punished, the rate of payment remains low. For example, only three houses in the Kuna Nega neighborhood of Corregimiento Kuna Nega pay for water, and only one household of Genesis (Appendix B). Since the government does not allocate additional funds to IDAAN, often investing in more profitable and visible projects like the Canal expansion, the water agency struggles to achieve its goals.

Another major issue that complicates the transportation of water to rural communities is the unique topography of the landscape. As seen in Figures 2.8 and 2.9, many of the rural neighborhoods of Corregimento Kuna Nega are built on steep terrain and in hard-to-reach places. Providing up-to-date pipework and other infrastructure necessary to pump water to rural communities has been a great challenge due to the long distances between nodes with variable inclines of unpaved roads (Erickson, 2017). While pumps are powerful devices, pumping water uphill requires high pressures because water loses pressure when it travels uphill. The infrastructure necessary in this hilly area is therefore costly and difficult to maintain, compared to the flat land of the city.

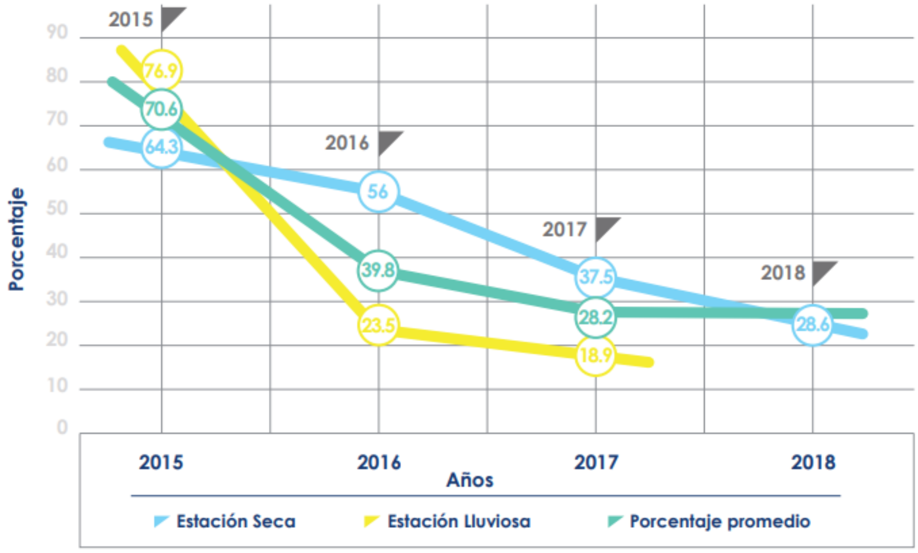


Figures 2.8-2.9. A view of one portion of the neighborhood found near the peak of the Kuna Nega area (above) and a topographical map of the area being studied (below).

Another recent challenge that IDAAN faces is rapid population growth. Between 2014 and 2021, the population in Panama increased by about 394,000, which is a nearly 10% increase in total (United Nations, 2022). The majority of the total population of Panama resides in the Province of Panama – more specifically in Panama City and San Miguelito (*Panama - The World Factbook*, 2022). In the rural neighborhoods of Corregimiento Kuna Nega, many houses resemble Brazil’s favelas because they are made of salvaged and scrap material from the nearby dumping areas (Figure 2.10). Whether from planned projects or illegal housing settlements, rapid population growth in the metropolitan area increases demand for clean water and puts a strain on the outdated aqueduct system (Erickson, 2017). In many communities, this increased demand from population growth has recently hampered the organization's development of a proper infrastructure plan.

Figure 2.10. A home built from scrap metal gathered from the neighboring Patacón Waste Plant

Additionally, as water travels from the treatment plant to homes of residents, deteriorating water quality is a growing issue. Coming from the treatment plant, the water has gone through multiple quality tests and is sufficiently potable. However, once the water travels through the system's pipes in Corregimiento Kuna Nega, the water often becomes contaminated. During the rainy season especially, water quality decreases in this region because runoff mixes with contaminants and then enters water sources. This rampant pollution can be observed on a larger scale as well, as deteriorating water quality is increasing among many of Panama's water sources (Figure 2.11). Due to dumping fees at the nearby Cerro Patacón Sanitary Landfill, the neighborhood has become an illegal dumping site where trash is piled high without regard for the surrounding environment or human life. Since this land is owned by the government and not owned by the people who live there, there is little pressure on the government to provide proper sanitation services in the area. While it is a difficult task and progress is slow, the government has entrusted IDAAN to address these issues.



GRÁFICA 32. **CALIDAD DEL AGUA DE LOS PRINCIPALES RÍOS DE PANAMÁ (PROPORCIÓN DE RÍOS CON UNA BUENA CALIDAD DE AGUA): AÑOS 2015 - 2018**

Fuente: Ministerio de Ambiente.

Figure 2.11. A graph describing the decline in "Water Quality of the Main Rivers of Panama" provided by the Environmental Ministry of Panama ("Voluntary National Review," 2020, p. 251).

As a result, this trash remains and poses health risks to residents as it pollutes local streams that some residents use as a principal water source (Figures 2.12-2.14). Even in designated areas, where it is legal to dump trash, such as The Cerro Patacón Sanitary Landfill, improper containment practices allow chemicals to leach into local water sources. This pollution can affect the quality of the water if it enters the water piping system. Although IDAAN ensures good water quality when it leaves the water treatment plant, residents and some IDAAN engineers that we interviewed will not drink the water that comes to their homes as piles of trash contaminate the streets where the pipes run and fill manholes where valves are located.

Figures 2.12-2.14. Examples of the degree to which garbage is present in these areas along the streets and in access points where it is in direct contact with aqueduct pipes.

IDAAN is trying to fix these distribution issues to ensure the safety of residents across Panama. The agency's mission, from their *Misión Y Visión* webpage, is to improve the health of the community through the provision of potable water services and the gathering and disposal of sewage. Dedicated to environmental conservation, IDAAN's vision is to be the enterprise leader of public services in Panama and to reach levels of productivity and profitability that allow them to be self-sustainable and to identify new projects (*Misión Y Visión – IDAAN WEB*, 2021). These new development opportunities include their current efforts to build a new connection between the Patacón pump station and Corregimento Kuna Nega.

While mostly functional, the current infrastructure is old and in need of constant repairs and maintenance. When we asked about the current process IDAAN has in place to get rid of the waste produced from the treatment plant in Chilibre, they said the waste treatment plant that once processed this waste had collapsed. Since it was too expensive to fix, IDAAN abandoned the project. In recent years, they have been dumping waste locally without treating it. In the treatment plant itself, one of the pumps recently cracked under its own weight and is being repaired. Since the organization does not have any backup pumps of that size, the amount of water produced by the plant has been decreased until it can be repaired. To keep water delivery consistent, the agency would benefit greatly from developing a more robust emergency plan.

2.5 Water Delivery Methods

Current methods of water delivery are based on three main methods of water supply: demand, continuous flow, and rotational (Gonzalez 2020). Demand supply is the most sophisticated of the three, but it requires several points to be met to establish water equity. Examples of these requirements include sufficient Canal capacity for simultaneous water demand in one area, regulatory storage to provide water in a timely manner, and major storage reservoirs and pump capacity. This method of water supply is the most ideal, albeit expensive and mechanically demanding, among the three as it provides water storage that is regularly managed by the supplier rather than on an individual basis where improper storage methods can result in a higher rate of low water quality (Gonzalez 2020). This option is not currently a possibility for the Corregimiento Kuna Nega because the current infrastructure is not sophisticated enough. With more funding, it may be possible, however, this delivery method relies on a mass supply of clean drinking water that may not be available in nearby lakes and freshwater sources.

The continuous flow method establishes a system where a constant flow of water is supplied to different regions based on a standardized volume of water required per unit of land space. This method is less ideal than demand-supply as it is susceptible to higher rates of water leaching when being delivered to areas that require lower volumes of water, such as residential areas. In addition, the irrigation systems and containment systems must be consistently watched by the landowners to make sure that the water is being supplied at the proper rates without leaks (Gonzalez 2020).

The third option, which is used in many underserved areas, is the rotation water supply system. Under these conditions, residents of certain areas are allowed exclusive access to a common water source, or “Rotation Block”, for a certain period (Gonzalez 2020). Once everyone has acquired their proportional share of the water, the cycle repeats (Bishop & Long, 1983). This method is employed in areas where networks are overloaded with demand from consumers due to minimal infrastructure or high population growth rates. Although this method provides some aid, it is not optimized, and it has salient flaws. The amount of water distributed and the times at which it is distributed differs from consumer to consumer, which creates equity problems. In Gonzalez’s study, Area 3 utilized this method, and the data show how irregular access to water promotes dangerous water storage techniques which are harmful to the residents’ health (Gonzalez 2020). When a region resorts to using a scheduled water delivery rotation, it is more than likely due to a lack of funding and infrastructure. These areas will also likely fail to maintain the schedule as designed as population grows and infrastructure degrades. Residents inevitably require water from supplemental sources, be they deliveries from water tank trucks or resorting to gathering from natural untreated water sources.

Around 2014, IDAAN designed and built the Chivo Chivo pump station to supply Chivo Chivo, Lucha Franco, Villa Cardenas, Kuna Nega, and el Valle de San Francisco utilizing the rotational delivery system. They estimated that the pump station would be able to provide water to the region until 2035 when it would need to be redesigned or upgraded to accommodate population growth. As the district is located in the greater metropolitan area of Panama City, it experienced this population growth to a greater degree than other far more rural areas of the nation. In the past eight years, the growth of the population has vastly exceeded the projections made during the design process of the Chivo Chivo pump station, and thus, many people now live in the region with little to no access to consistent and predictable potable water. As the current situation stands, one resident informed us that the Villa Cardenas region has access to water on Wednesdays, Saturdays, and Sundays, which vary, and supplemental water is provided on some off days from tank trucks which carry water. On the other hand, the Kuna Nega and Valle de San Francisco only receive water on one day out of the week for most of the year. These tank trucks pump water through the network through a hookup, as seen in Figure 2.15, and deliver water in containers in the most difficult to reach places.

Figure 2.15. An input line for the tank trucks that deliver water on days where no water is available from the network. Upon closer inspection, it is uncapped and open to the elements with a pile of dirt easily visible from the outside.

The lack of access to a consistent water supply consistently holds back the residents of Panama. Water is a vital resource to daily life beyond drinking. It is also used for other residential purposes like plumbing, washing, and cooking. The national standard estimation, used by IDAAN and countries like the US, is that each person uses approximately 100 gallons of water throughout their day on the previously mentioned tasks. Although, the system should still be able to support a higher demand beyond this estimation. Water is also used in industries such as schools, hospitals, textile manufacturing, and sugar and paper mills, all of which are common throughout Panama. Water is also a necessary component to the agricultural industry, which affects the livelihoods of many Panamanians. In a 2018 report from the Embassy of the Kingdom of the Netherlands in Panama, an estimated 6% of Panama's population are directly employed as "farmers in agriculture, livestock, hunting, forestry, fishing, and related service activities" ("Agriculture in Panama," 2018). The embassy approximates that 18% of Panama's population is indirectly employed in these occupations. Of the three industries, agriculture remains the most water demanding across the world, accounting for about 70% of the world's freshwater demand ("Voluntary National Review," 2020. p.124). A steady supply of water for these industries is an incredibly important part of keeping society employed and efficient.

2.5.1 Effects of Water Delivery Methods on Quality

In 2020, Carlos Gonzalez published findings regarding the water quality in storage containers in the Arraijan District of the Western Panama Province of Panama. Located just 9 miles southwest of Kuna Nega, residents in Arraijan experienced a variety of water cleanliness levels which fluctuate depending on the delivery schedule of clean water to the area. Variables that affect the delivery schedule include the amount of supply that IDAAN has available and the demand that other neighborhoods place on the system. Out of four areas researched, Areas 1 and 2 experienced continuous water supply and occasionally intermittent water supply, respectively.

In these areas, Gonzalez observed that the water stored in homes showed better quality levels compared to samples taken from Areas 3 and 4. After testing chlorine levels, turbidity, coliform count, E. coli presence, and HPC, Area 1 performed the best with most water containment systems presenting safe levels of each respective category. On the other side of the spectrum, Area 3 displayed the highest use of unsafe water containers and lowest levels of water quality. At the same time, Area 3 had the most infrequent schedule of water supply, averaging 96 hours/week, which means that water flowed to Area 3 for a little over half of the week.

By rationing the water supply to this degree, residents are encouraged to stockpile their water by any means necessary. As seen in Figure 2.16, this rationing facilitates the use of improper storage containers and unsanitary preservation practices such as collecting rainwater in unclean containers (Gonzalez 2020). Figure 2.17 shows a typical water storage tank in the Corregimiento Kuna Nega neighborhood. Unregulated, these tanks foster the growth of harmful waterborne illnesses and serve as breeding sites for disease vectors like mosquitoes. Such waterborne illnesses include typhoid fever, cholera, leptospirosis, hepatitis A, and Giardiasis, which is particularly predominant in Panama (Pineda et al., 2010). According to the National Library of Medicine, Diarrhea is still a leading cause of death, particularly in infants and children, with “about 88% of deaths attributable to unsafe water, inadequate sanitation and insufficient hygiene, mainly in [the] developing world” (Mebrahtom et al., 2022). These data present a convincing argument that by increasing the amount of time that water is available to these regions, evidence of increasing water quality and containment practices will follow.

Figures 2.16-2.17. Examples of residential water storage tanks in Villa Cardenas and Valle de San Francisco where people store excess water and sometimes use their own pump systems to deliver it to their home.

Chapter III: Methodology

3.1 Section Overview

This chapter begins by describing the mathematics behind hydraulic modeling. To model the flow of water through the pipe network, EPANET requires input values for each node of the system. First, we mapped the network of the system, noting all junctions, reservoirs, tanks, emission points, and pipes. Each of these components corresponds to a component in the system's user interface. Then we found lengths, altitudes, demands, and valve schedules. Finally, we discuss the Patacón Connection.

3.2 Water Flow Mathematics

To deliver a comprehensive response, we had to understand the equations that IDAAN currently uses to deliver water through aqueduct systems. The main goal is to deliver water to the surrounding communities such that the needs of every person are met equitably. As a bare minimum, enough clean water must be supplied for plumbing facilities to function and for people to be able to properly drink, bathe, cook, and clean. By taking these requirements into account, we generated a more accurate simulation within the EPANET software.

The following mathematical principles are the basis of the EPANET software and services. In these equations, it is given that water is flowing from two arbitrary points "i" and "j". Total water demand (P_{ij}) is the sum of the point water demands, $q_{ij,w}$, between two nodes with "w" withdrawal points between the nodes. We define this relationship as:

$$P_{ij} = \sum_{w=1}^{n_{ij,w}} q_{ij,w} \quad (1)$$

Under these given conditions, the equation presumes that withdrawal points are generally equally spread across the length of the edge, or pipe.

The next concept to understand is that of head loss, Δh_{ij}. The interaction between the velocity of the water flowing and the resistance to flow exerted by the pipe walls or joints causes a decrease in "head", "pressure", or "energy" over the length of the edge. We represent this interaction as:

$$\Delta h_{ij} = H_i - H_j \qquad (2)$$

$$\Delta h_{ij} = rL|Q|Q \qquad (3)$$

These principles help establish the mathematics behind how water behaves in a system, but when used to model real systems, they often generate a significant amount of error with regard to head loss as they do not preserve the balance of all types of energy in the system, per the first law of thermodynamics. According to Menapace et. al. (2018), you can simplify the system equation and make programs like EPANET more reliable in cases where water demand is more uniform with the following:

$$\Delta h_{ij} = \int_0^{L_{ij}} r_{ij} Q_{ij}(x)^2 dx \quad (4)$$

where "r" is the hydraulic resistance per unit length, "Q" is the virtual flow along the length of the edge, and "x" is the distance from the initial node.

After defining the average demand required by the people of Corregimiento Kuna Nega, a system utilizing these principles could provide a more realistic and holistic solution for the engineers of IDAAN.

Pipes that transport water come in different sizes (diameters) and are made from different materials. The diameter and material affect the friction of the pipe. Pumps have to work even harder to keep the water flowing at a high enough pressure to overcome the loss of pressure due to high friction with pipe walls. The following equations calculate the water pressure loss due to friction with the pipe walls; they are ultimately used to determine the flow of water in a pipe, relating to its physical properties:

$$\text{Hazen-Williams Equation: } H_{loss} = \frac{4.73L(\frac{Q}{C})^{1.852}}{D^{4.87}} \quad (5)$$

$$\text{Darcy-Weisbach Equation: } P_{loss} = f\,\frac{l}{D}\frac{\rho V^2}{2} \quad (6),$$

where,

$$f = f(Re, \frac{\epsilon}{D}) \quad (7)$$

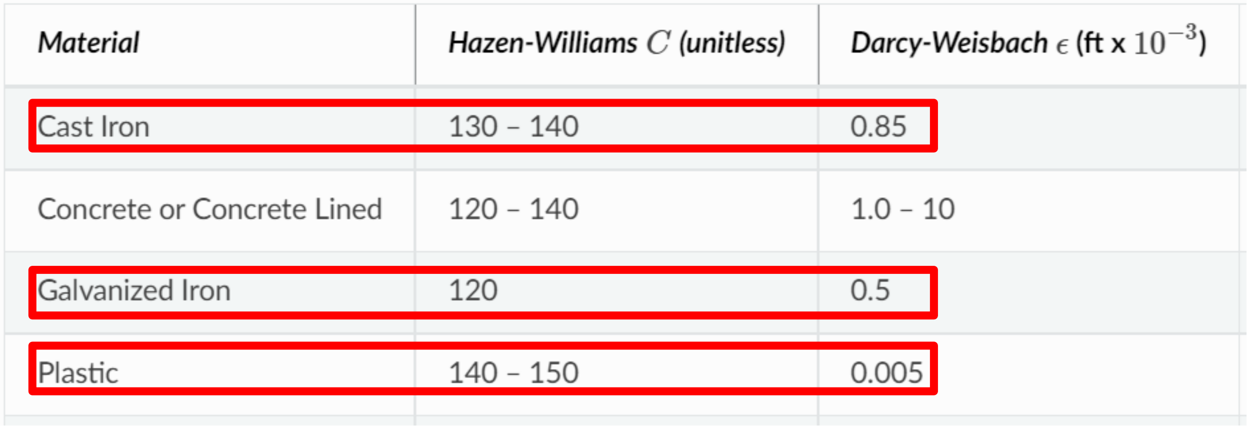
$$Re = \frac{4Q}{\pi D \upsilon} \quad (8)$$

The equations require different roughness coefficients. The Hazen-Williams coefficient is a unitless number that describes the friction caused by contact between water and the pipe. The Darcy-Weisbach coefficient describes the same thing, but has a different value, and has units of millifeet. The roughness coefficient depends on the pipe material and smoothness which are dependent on age and corrosion of the pipe. Water experiences more friction in cast-iron pipes than ductile-iron or PVC pipes. This increased friction causes less consistent flow rates. The true roughness coefficient also changes with age, as a pipe corrodes. Hazen and Williams note:

> The gradual roughening of the interior of cast-iron pipe is one of the most familiar of water-works phenomena. It is also one of the most difficult to compute. In a general way it may be said that is a series of years, which is not long compared with the total life of the pipe, the roughening of the surface and the reduction of the area through rusting and tuberculation reach such an extent that twice as much head is consumed in sending a given volume of water through it as was the case when the pipe was new (Hazen & Williams, 1910, p. 2).

However, we do not have enough information to complete a full study of roughness coefficients. For our purposes, an approximation is sufficient. Table 3.1, taken from EPANET's user manual, provides the necessary coefficient values for both equations. For the Hazen-Williams equation, we used values of 150 for PVC pipes, 120 for ductile (galvanized) iron, and

140 for cast iron. For the Darcy-Weisbach equation, we used values of 0.005 millifeet for PVC pipes, 0.5 millifeet for ductile (galvanized) iron, and 0.85 millifeet for cast iron. See Appendix C for further mathematics.



Material	**Hazen-Williams C (unitless)**	**Darcy-Weisbach ϵ (ft x 10^{-3})**
Cast Iron	130 – 140	0.85
Concrete or Concrete Lined	120 – 140	1.0 – 10
Galvanized Iron	120	0.5
Plastic	140 – 150	0.005

Table 3.1 Roughness Coefficients for new pipe based on material. Values for Plastic (PVC), Cast Iron, and Ductile (Galvanized) Iron pipes were used (The Network Model, n.d.).

Since both equations describe fluid flow, EPANET can run an analysis with either one. While the equations appear arduous, our only task is to input their corresponding roughness coefficients into the software, since EPANET solves them for us. We ran our model twice: once with the Hazen-Williams equation and once using the Darcy-Weisbach equation. We took care to use each equation’s respective roughness coefficients when creating both models. We then recommended an optimized schedule based on the model.

3.3 Data from Human Sources

The original scope of the project focused primarily on the collection and manipulation of data to objectively optimize the water distribution in the region. As our project progressed, there were fewer opportunities to obtain data directly from residents. If we had had more time, we planned on surveying people in the local community to determine how unreliable water supply affects their day-to-day life and what their preferred water delivery schedule would be. Unfortunately, time constraints kept us from pursuing this additional deliverable.

Although we did not have the opportunity to conduct formal community surveys, we heard first-hand accounts from individuals in the local community about the state of the system. We learned about when water is supplied to the homes of some individuals and contrasted that with the established schedule made by IDAAN at the Chilibre Water Treatment Plant. We observed that residents had access to water between one to three days per week depending on the time of year and location of their homes. In general, we learned that people in these neighborhoods have access closer to three times per week during the dry months of December to March and closer to once per week during the wet season which spans the other eight to nine months of the year. Furthermore, the days in which pipes or tank trucks supply water was inconsistent with the schedule we received from IDAAN. This disconnect between IDAAN and the local residents is likely due to the water not being pumped uphill with enough pressure to reach all of the houses. While IDAAN is delivering the water, it never reaches its destination because the pumps are not strong enough. We also learned that residents often do not trust the quality of the water enough to drink it, without first boiling or treating it.

3.4 Field Work

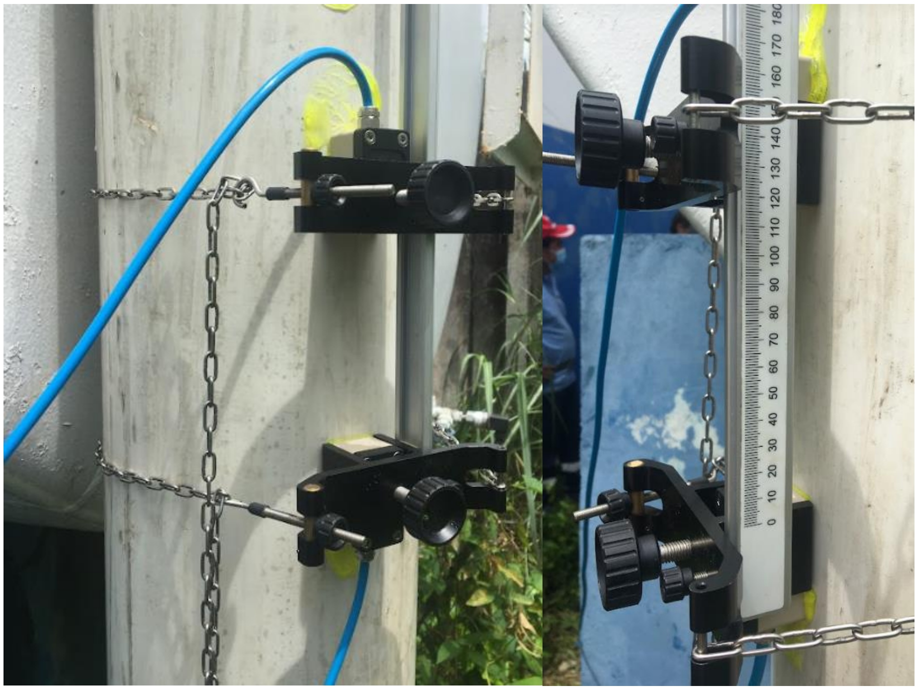
We traveled into the field to collect data almost every day of the work week for the duration of the term, and we collected the majority of our data in the field. To begin, we located the current piping infrastructure. While IDAAN does keep records of the pipes in the network, the information in their mapping software, ArcGIS, needed revisions. Maintenance, new projects, and damage affect current infrastructure, and IDAAN is not always aware of such changes. In the regions of the San Francisco Valley and Kuna Nega especially, IDAAN never recorded the main pipelines and their corresponding data, such as diameter and material. Our first field task was updating the agency's maps, so we could build onto our model.

To find information about pipes, junctions, pumps, and tanks, we worked with Enrique, a sanitation engineer at IDAAN who has worked there for over 25 years and thus possesses a wealth of knowledge about the water distribution system in Panama City. Since the pipes in Corregimiento Kuna Nega are only half buried, we were able to follow the pipes by driving or walking in hard-to-reach areas, as seen in Figure 3.1. Enrique was able to point out where these lines ran and their respective specifications. On a paper map of the neighborhood, we drew the paths and noted the diameter and material of each pipe (Appendix B).

Figure 3.1. A pipe from which we gathered information, such as location, diameter, and material. We were able to walk alongside the main road to gather information about these pipes.

Pipes have two diameters: an internal diameter, which is the hollow space through which water flows, and an external diameter, measured from the outermost edges of the pipe. The internal diameter is relevant for our analysis because water flow is the focus of our study, not its interactions with the environment. Using a tape measure to determine each pipe's internal diameter in the network would be cumbersome. Instead, we expedited data collection by consulting Enrique, who is familiar with IDAAN's pipes and could recognize the interior diameter of the pipes at a glance. We also confirmed these values upon visiting the Chilibre Treatment Plant where we checked the dimensions of the pipes that are used in the system. Once we collected all the pipes' locations, diameters, and materials from the field, we input this information into IDAAN's ArcGIS online database, thereby updating the agency's plans.

We then moved onto recording the flow rate of the water coming in and out of the Chivo Chivo pump station. We also recorded the flow rate of the water passing through a few valves in our system. We recorded these flow rates in locations throughout Corregimiento Kuna Nega so that we could get a holistic image of the system. There are two general approaches when recording water flow in a pipe: inside or outside measurement. Since there was no equipment available to take measurements from inside the pipe, we measured from the outside. To record the flow rate this way, we used transit time ultrasound sensors. In this method, two transducers (sensors) are glued on to the outside of the pipe parallel to one another (Figure 3.2). The two transductors must be placed a certain distance apart for optimal readings (Figure 3.3). This distance is calibrated by the flow meter software based on certain field conditions. The transducer placed upstream transmits sound to the downstream transducer, which receives the signal. Together, they "measure the time it takes for an ultrasonic signal transmitted from one sensor to cross a pipe and be received by a second sensor" (*Outside Pipe Flow Measurement Technologies*, 2012).

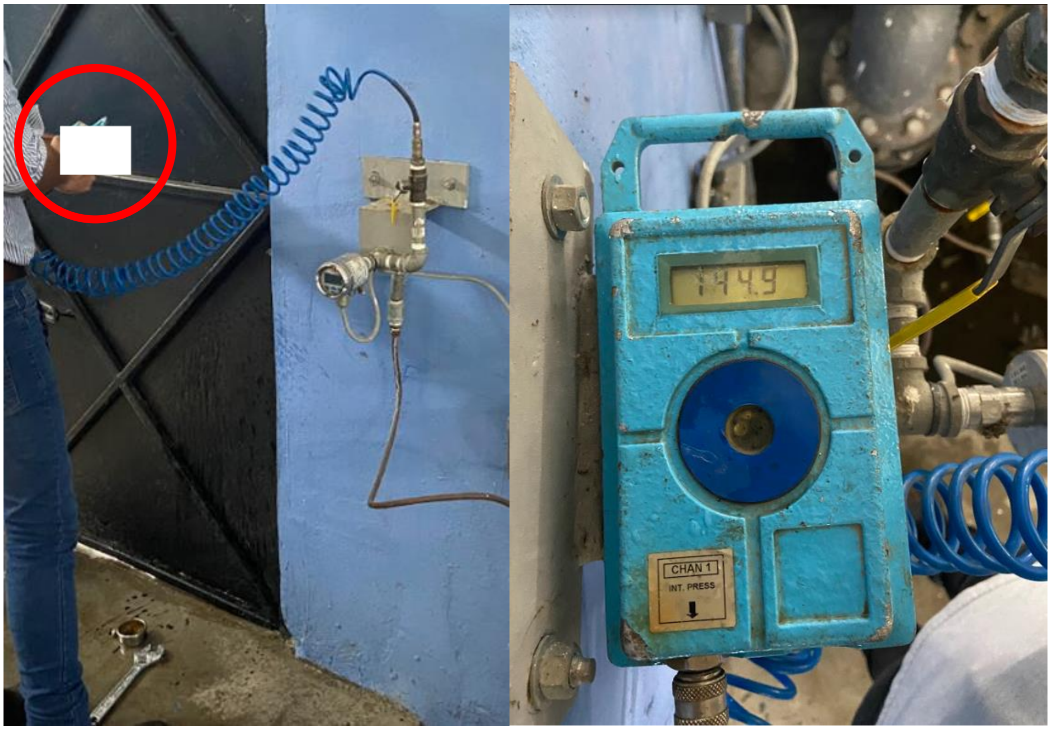


Figures 3.2-3. The setup for the flow meter measurements. With the help of IDAAN's engineers and workers, we operated these devices to measure flow rate, in gallons per minute.

As seen in Figure 3.4, these transductors directly connect to the flow meter reading device, using blue and red tagged cabling that corresponds to downstream and upstream flow, respectively. Once connected, the flow rate is displayed on the reading device in gallons per minute. Using the recording function on the flowmeter, we collected the flow rate traveling in and out of the pump station, as well as the flow rate at tanks and valves in various locations for periods of approximately 15 minutes.

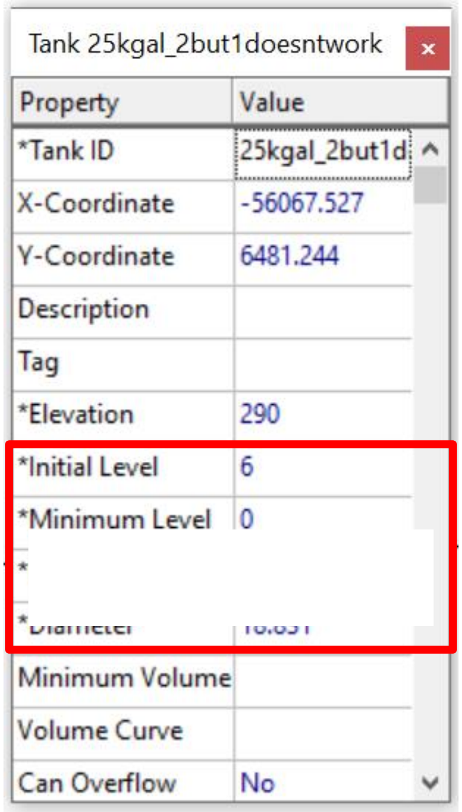
Figure 3.4. The flow meter reading device, displaying flow rate in gallons per minute (GPM).

Next, we measured pressure along various points, or junctions, in the water network. We measured pressure using a hand-held pressure gauge. This device connected to the water supply by a cable and displayed the water's pressure, in pounds per square inch (psi). In some locations, such as in the pump station seen in Figures 3.5 and 3.6, we measured pressure for a duration of approximately 15 minutes. We justified this short recording period because the pressure remains the same at this point due to the pump's consistent power. However, in other locations it was necessary to measure pressure for longer periods, because the pressure values in those regions can vary greatly over the course of a week.



Figures 3.5-3.6. The setup for the hand held pressure gauge, circled in red, (left) and the pressure reading in psi (right).

While we were in the field, we also recorded each tank’s volume. Most tanks were 25,000 gallons, or 3342 ft^3. Because EPANET does not have a straightforward input for volume, as seen in Figure 3.7, we had to calculate the diameter that would correspond to this volume, with respect to the tank’s height. Using a tape measure, we found that each tank had a height of 12 feet.



Tank 25kgal_2but1doesntwork

Property	Value
*Tank ID	25kgal_2but1d
X-Coordinate	-56067.527
Y-Coordinate	6481.244
Description	
Tag	
*Elevation	290
*Initial Level	6
*Minimum Level	0
*	
*Diameter	18.831
Minimum Volume	
Volume Curve	
Can Overflow	No

Figure 3.7. The window where tank inputs are entered into EPANET. The boxed information, in red, are the relevant volume inputs.

EPANET assumes water tanks are arranged vertically, so their base touches the ground. Since our water tanks are cylinders, arranged horizontally, height corresponds to tank level. A tank height of 12 feet and a diameter of 18.831 feet correspond to a tank volume of 25,000 gallons. To calculate this diameter we used the volume of a cylinder equation:

$$V = \pi(d/2)^2 h \qquad (9)$$

$$3342.0139\ ft^3 = \pi(d/2)^2(12\ ft)$$

$$d = 18.831\ ft$$

The exception to these calculations is the Santa Librada tank, which holds a greater volume of water, at 300,000 gallons. To input this tank's information into the model, we calculated a different diameter and assumed a different tank height, of 65.232 ft and 12 ft, respectively. However, this tank's water level is so low, because the water exits the tank as quickly as it enters, that we were not able to measure flow and pressure values. We could not get a signal registering that any water was passing through the tank's supply and withdrawal pipes. We could have used previous data that IDAAN has collected on this tank, using 1030 gal/min as an estimated flow rate, but it would be an inaccurate representation of the current infrastructure.

To better represent the current infrastructure, we measured pipeline lengths. EPANET does not require the precise location of any node, as the elements are placed in an arbitrary blank field, but it does require the length of pipes between nodes to make accurate calculations. When this length is not recorded, the precise location can be used to calculate the approximate length of the pipes. Google Earth has a tool where the user can drop pins along a path, displaying the lengths of the individual sections as well as the total length (Figure 3.8).

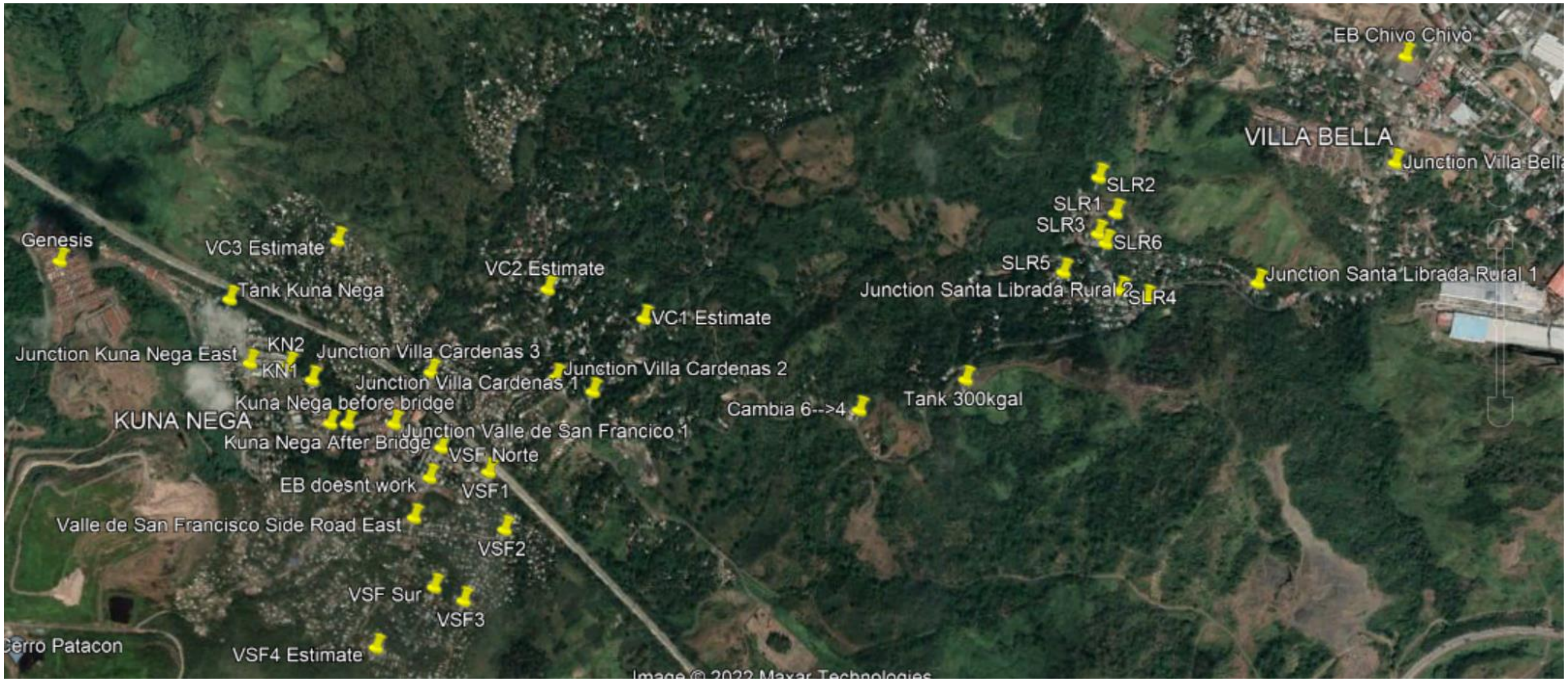


Figure 3.8. We used Google Earth to estimate the total length between nodes

We used this tool, along with geolocation-tagged photos and points noted on paper maps to measure the length between nodes. When necessary, we determined the locations of certain model components by visiting them in the field with a GPS system on a cell phone to record location, distance, and more.

We then moved on to find the elevation of each tank and junction. At first we used Google Earth. With a topographic satellite view of the entire globe, determining the elevation of tanks and junctions was as easy as hovering a cursor over the point in question. However, IDAAN informed us that these elevations are not very accurate. To remedy this, we went out into the field to gather as many elevation points as we could. The elevations for about half the nodes in our model are from data gathered in the field, and the other half were found using Google Earth. Since our time to gather this data in the field was limited, we chose to prioritize data collection at the main components of the system.

To measure elevation in the field, we used an altimeter. To set up the device, we placed the altimeter on the ground where it was level with the object. An altimeter measures elevation by communicating with a satellite, which sends a signal down to the device and waits for the device to send the signal back. The device computes elevation based on the duration of the satellite-to-surface round trip (Chelton et al., 2001). Cloudy skies block communication between the device and the satellite, and slow down data collection. Some tanks were raised above ground level by water towers. For these, we estimated the height from the ground to the base of the tank, which we added to the measured elevation. The device also produced a precision value for each elevation measured.

Figure 3.9 The altimeter device that measures elevation, in feet.

3.5 EPANET

EPANET, the Environmental Protection Agency Network Evaluation Tool, is an industry standard modeling program used to design, understand, and optimize fluid flow systems, and it is the software we used to create our hydraulic model of the system. EPANET is an open-source computer program used by many organizations to model water delivery systems. Developing countries often use this software since it is easy to use but offers a lot of power. It prompts the user to create a network of all junctions, pipes, tanks, and pumps in the network. The physical properties of the network are then entered into the model so analyses of the system can be run.

These properties are:

- The length, diameter, and roughness coefficient of each pipe;
- The volume, base area, and elevation of each tank;
- The elevation of each junction;
- Demand by junction;
- The status of each pump, described using scripts;
- The pump curve of each pump.

More information can be provided to the system to generate more dynamic analyses. For example, the leakage from each pipe is input by adding the amount of water lost to the total demand. Beyond leakage, adding additional information into our model is not necessary.

As seen in Figure 3.10, the user interface consists of a large window, the Network Map, a sidebar window, the Browser, a series of dropdown menus along the top of the window, and a toolbar just below the menus.

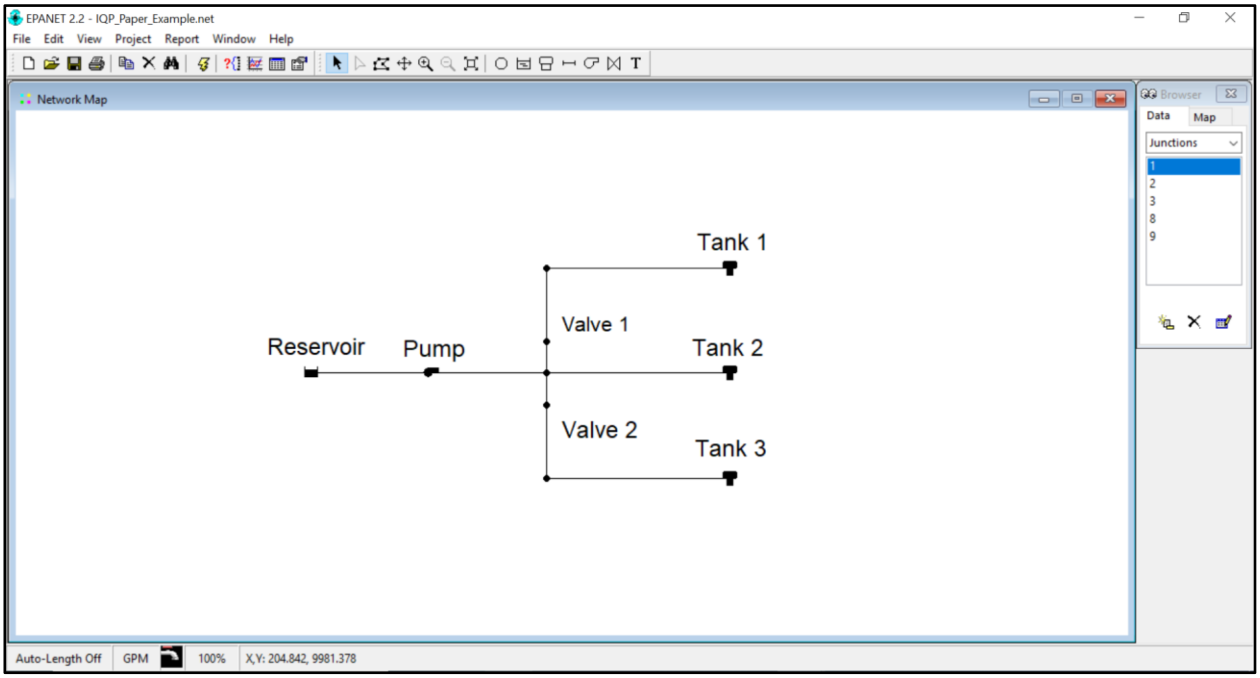


Figure 3.10. A window capture of the EPANET program with a sample fluid system map generated to provide a basic overview of what can be done in the program

There are six main components that generate a vast array of delivery maps for any application. These are, in order of appearance in the toolbar: junctions, reservoirs, tanks, pipes, pumps, and valves. For each of these map components, a properties menu can be displayed and filled with data to set up for a system analysis (Figures 3.11-3.13).

Tank 5

Property	Value
*Tank ID	5
X-Coordinate	8000.000
Y-Coordinate	7000.000
Description	
Tag	
*Elevation	0
*Initial Level	10
*Minimum Level	0
*Maximum Level	20
*Diameter	50
Minimum Volume	
Volume Curve	
Can Overflow	No
Mixing Model	Mixed
Mixing Fraction	
Reaction Coeff.	
Initial Quality	
Source Quality	
Net Inflow	#N/A
Elevation	#N/A
Pressure	#N/A
Quality	#N/A

Pipe 14

Property	Value
*Pipe ID	14
*Start Node	Cambia64
*End Node	JunVC1
Description	
Tag	
*Length	3492
*Diameter	4
*Roughness	150
Loss Coeff.	0
Initial Status	Open
Bulk Coeff.	
Wall Coeff.	
Flow	#N/A
Velocity	#N/A
Unit Headloss	#N/A
Friction Factor	#N/A
Reaction Rate	#N/A
Quality	#N/A
Status	#N/A

Pump 6

Property	Value
*Pump ID	6
*Start Node	4
*End Node	3
Description	
Tag	
Pump Curve	
Power	
Speed	
Pattern	
Initial Status	Open
Effic. Curve	
Energy Price	
Price Pattern	
Flow	#N/A
Headloss	#N/A
Quality	#N/A
Status	#N/A

Figure 3.11-3.13. Examples of various property menus within the program. White value boxes on the right-hand column of the menu indicate where data can be input, and yellow value boxes indicate where data is output.

As mentioned above and seen in Figure 3.13, EPANET requires an input for Pump Curve. The pump curve is a graph that describes the strength of a pump. Pumps increase the pressure of water, so water leaving the pump has a greater pressure than the water entering. This increase in pressure depends on the flow rate. Imagine someone paddling a canoe. When the boat is stopped, the canoer can put full strength into paddling because the canoer is pushing against stationary water. But when the boat is moving quickly, the canoer is paddling with water moving in the same direction. The canoer must move the paddle faster than the water, which makes it harder to use full strength. Similarly, a pump pushing slow-moving water increases pressure more than a pump pushing fast-moving water. A pump curve reflects this phenomenon.

On the x-axis is volumetric flow rate; on the y-axis is the pressure. On the curve, there are three solid lines that each correspond to the size of the impeller (rotating component of the pump). These lines represent the maximum pressure increase for each possible flow rate, and the U-shaped lines represent the efficiency of the pump for each possible pressure and flow rate. As seen in Figure 3.14, the pumps at the Chivo Chivo Pump Station are most efficient using the largest impeller (9.33 mm in diameter) when the flow rate is 950 GPM. At this flow rate, the pumps increase the pressure by 70 feet of head per stage and have an efficiency of 84.5%. Figure 3.15 illustrates the pump curve as input into the EPANET model.

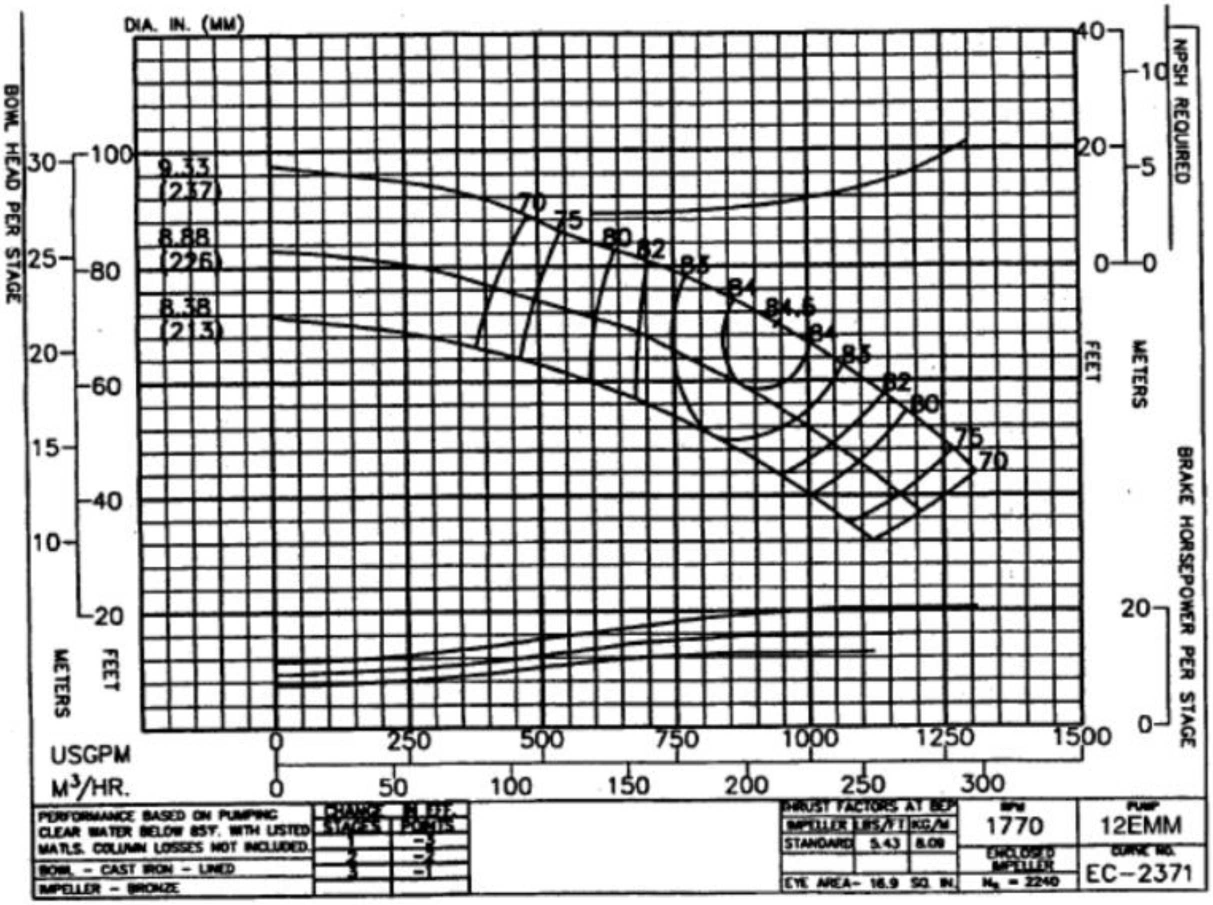
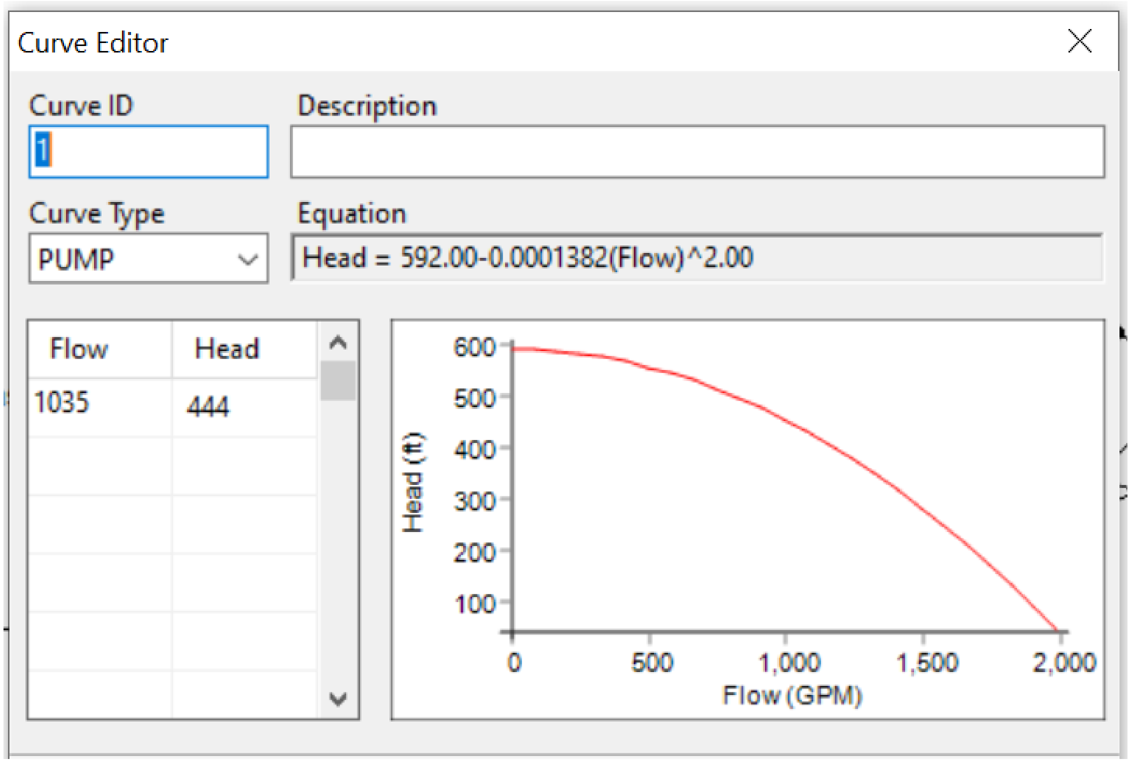


Figure 3.14. The Chivo Chivo Pump Station Curve.



Curve ID
1

Curve Type
PUMP

Equation
Head = 592.00-0.0001382(Flow)^2.00

Flow	Head
1035	444

Figure 3.15. The Chivo Chivo Pump Station Curve as input into EPANET.

Once all the values for the system are entered into the nodes and links, the user can use the “Run Analysis” button in the Project menu, and the yellow output boxes in the properties menus populate with results for the given system configuration. In our project we are mainly utilizing the change in valve status and presence of any extra pumps to optimize the delivery state. This model, along with our report, is our main deliverable to the IDAAN optimization engineering team.

According to the local engineers, EPANET is not as commonly used within IDAAN as it is in other countries and companies because their efforts in improving the systems are usually reactive instead of proactive. Our use of this program created a structure for them to be able to use in the future if they want to further refine the system and would save them the time needed to establish this model. The model could even be used to predict future issues and deal with emergencies.

In essence, the generation of our EPANET model comes down to the determination of the following three main factors: Demand, Leakage, and Scripts. These factors determine the efficacy of our model and heavily influence our conclusions based on our findings.

3.5.1 Demand

Demand is the number of gallons of water households need every minute. In some parts of the city, the amount of water used is determined by a meter and then charged by the gallon. If the homes in Corregimiento Kuna Nega were metered, we could use data from the meters of a random sample of the houses to determine the total demand of each pipeline. However, there are no meters in this region, so homeowners are charged a standard rate each month.

To understand demand in terms of the EPANET model, we must specify that a model is composed of links and nodes. Pipes and pumps are links. Tanks and junctions are nodes. Each link is connected to two nodes. Together, links and nodes create a network, which maps an entire water supply system. Our EPANET model maps one tank of the Chivo Chivo pump station and all the tanks, pumps, pipes, and houses supplied by that tank. EPANET defines demand as a property of junction nodes. The aggregate demand of a junction is the sum total of all upstream houses' demands.

With the growing population in Corregimiento Kuna Nega, water demand is increasing rapidly. As a result, the estimated water demand for the region must be recalculated to ensure that the appropriate portion of water is allocated for the region. The IDAAN engineers instructed us to follow their established estimation techniques by counting visible houses in the area using Google Earth's satellite view to estimate the number of houses supplied by each junction. We divided the map into regions, with one region representing each junction. All the houses in one region counted towards the demand for that junction. To ensure that we have a more accurate data set, each team member ran a separate house count so we would have data in triplicate. From there we took the average of our values and used that as our metric that we would strive to meet. This preliminary house count was one of our first deliverables for IDAAN which ensured that we were on track to meet our goals

While inputting demand into the EPANET model, we realized that the software requested input for demand at each junction node. This meant that we needed another house count with different regions than were originally defined by IDAAN. To do this recount, we employed the same methods as described above, but instead of counting houses within region bounds, we counted in the area surrounding each pipeline. Using Google Earth, we counted the number of houses that branch from each main pipe in our EPANET model. We followed the pipes along main streets and included the houses which they seemed to supply in our count. However, because we were not given a map with clear lines of demarcation showing which houses belong to which nodes, like the one in Appendix B, it was not always clear which houses were correlated to each junction. This method results in a total demand value at each pipe that represents the demand of a section of a neighborhood. As opposed to the preliminary count, these data were just for our own use, and not a deliverable for IDAAN.

From this step, IDAAN recommended that we use a value of five people per home using 100 gallons of water per day as a standard metric for determining the current total water demand. Although these are the standard values observed by IDAAN and used in their last demand estimate of the region (July 2019), we remained skeptical about its accuracy (see Appendix C for report). After all, the area is undersupplied because of a previous error in estimating demand.

During this process, we recognized several limitations. Primarily, due to the densely forested nature of the landscape, we found it difficult to accurately identify all homes because these informal houses are often located in very close proximity to each other, it was difficult to interpret where one house ended and where the next began. To mitigate counting errors, we coded each square of visible roofing as one residence, with a change of color indicating a new residence. Having spent a great deal of time in the field, we were able to recognize the areas we were analyzing which helped to some degree as well. Another limitation of our census method was the quality of the images provided on Google Earth and the weather patterns of the area. We found that clouds obscured a large region of the Kuna Nega and Genesis neighborhoods in the most recent Google Earth satellite pictures. To avoid missing houses, we used the timeline feature in the program to go back one step in time to the last instance where clear photos were taken. This strategy visually confirms more homes that were obscured by cloud cover. Because the population grows so rapidly in Panama, we noticed that some of the homes we had previously counted using the 2020 satellite pictures did not exist when using the 2019 pictures.

We recognize the limitations to current methods of determining total water demand where the methods could be improved, but this method proved to be our best option given our timeline and budget. The ideal option would be to go into the neighborhood in-person and determine population manually similar to a census, but that process itself would likely take longer than our project duration to accomplish all of our tasks. In regard to using census data to determine the total local population, the data provided by the National Institute of Statistics and Census for Panama only provides population values with detail down to the district and has not been updated since 2010. Because the study area is located in a mixture of rural areas that span between the districts of Panamá and San Miguelito, these values were of little help.

The same limitations detailed above apply to our second house count. In the second house count however, an overestimation of demand in one node would likely occur because we misinterpreted which houses are supplied by which main pipes. If there is an overestimation in one junction, that likely means that there is an underestimation in a nearby one. This overestimation, could result in unnecessarily high pressure, while the nearby underestimated region could not receive enough water or pressure to deliver a portion of their required water. The same is true for underestimations. In the event that demand is underestimated, as it was when IDAAN designed the Chivo Chivo Pump Station, the region will encounter the same problem it is experiencing now in just another few years. Despite being less of a problem than underestimating, overestimating will result in wasted economic resources that could be used for long-term maintenance. We tried to develop our own method with the best tools at our disposal to determine total water demand. It is unlikely that our estimates were so off that pipes burst, but it is possible the demand in each junction of our model is off.

3.5.2 Leakage

As mentioned in section 3.5, EPANET software assumes no leakage in its models. To input leakage into the model, we must consider leakage as demand. Therefore, the demand we enter for each junction is equal to the true demand of all houses connected to the upstream pipe plus all leakage from the upstream pipe. Although pipe leakage is our primary concern, leaks can also occur in tanks and pumps, which increases water loss.

It is difficult to directly measure the total water lost by leakage from pipes. The nine miles of pipeline we studied were mostly buried. It would be impractical to measure leaking water along the entire piping system. According to the engineers at IDAAN, there are two ways to estimate leakage: directly and indirectly.

Direct measurement requires a container to capture water that is leaking from a pipe. A leak can be directly measured by placing an empty container under the source and time how long it takes the container to fill. The leakage is the container's volume divided by the time to fill the container. On rainless days, leaks are easy to spot on exposed pipes because water can be seen dripping out. Leaks from buried pipes are also usually visible because water pools above the pipe, and bubbles can often be seen coming from the dirt. By identifying and measuring all leaks along a length of an exposed pipe, we can approximate the leakage per mile of pipe.

Indirect measurement is a simpler alternative and is based on the principle that the same amount of water enters and exits a pipe. In a closed system, mass can neither be created nor destroyed. That means that whatever volume of water goes into a pipe must come out. If the volume of water leaving a pipe is less than the amount entering, there must be a leak in the pipe. The leakage is therefore equal to the difference between the flow rate of water leaving and entering.

These methods of estimating leakage are subject to the assumption that each pipe experiences the same leakage per mile. Since pipes vary in pressure, velocity, and diameter, differences will be found in leakage along the length of each pipe. Another limitation to this assumption includes how some piping materials are more prone to leaks than others. PVC pipes are most likely to leak at cracks where the pipes join their fittings, while cast iron pipes are more likely to leak from corrosion and external damage (*Leak Potential for Different Kinds of Pipe,* n.d.). While the three methods above present potential limitations, they represent the best means of estimating leakage. Ultimately, due to time constraints, we decided not to employ any of these methods and to instead assume that there is no leakage in our model per IDAAN’s recommendations.

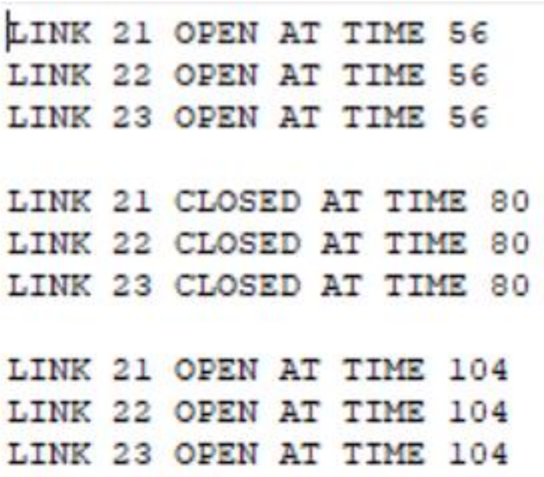
3.5.3 Scripts

Corrigemiento Kuna Nega is supplied by a rotational water delivery system. The delivery schedule outlining the days each neighborhood gets water can be found in Appendix B. By opening and closing valves according to a fixed schedule, engineers control which neighborhoods receive water. Kuna Nega should be receiving water on Sunday, Monday, Tuesday, and Thursday because the valve on the pipeline that supplied water to Villa Cardenas is closed then. Similarly, the valves to Kuna Nega are closed on Wednesday and Saturday, so Villa Cardenas should receive water on those days.

One possible schedule is to leave all valves open at all times. However, with the current infrastructure, this schedule would lead to supply problems. If the valves leading to each neighborhood were always open, houses at the tops of hills would never receive waterk, while houses near the tanks would experience no supply or pressure problems. The pumps in the Chivo Chivo station simply cannot propel water up such high elevations. In addition, the houses furthest away from tanks are the last to receive water. Even when pumps are strong enough, if flow rate is less than demand, houses farther from tanks will only be supplied if there is water leftover. This schedule is therefore not recommended for Corregimiento Kuna Nega given its current state.

The rotational system allows residents in the most remote sections of Kuna Nega to receive water. While there may not be enough water to supply all of Corregimiento Kuna Nega, there is enough water to supply all of Valle de San Francisco. The whole of Valle de San Francisco is supplied when valves to every other neighborhood are closed. On another day, only Villa Cardenas is supplied. Put simply, water can reach either Kuna Nega or Villa Cardenas, but not both.

Due to weak pumps, high demand, and high leakage, taps are often dry even on days when water is scheduled to flow. Residents remain unaware of when they will receive water and have to plan their lives around when they may receive water. A consistent schedule would allow residents more freedom in their daily lives. We expect our model to help for this reason. The modeling software possesses a feature which represents the opening and closing of valves. We entered the time each link would open or close into the EPANET model in a format similar to a computer script (Figure 3.16). For example, to close the valve at Pipe 12 one day into the simulation, we typed “LINK 12 CLOSED AT TIME 24.”



```
LINK 21 OPEN AT TIME 56
LINK 22 OPEN AT TIME 56
LINK 23 OPEN AT TIME 56

LINK 21 CLOSED AT TIME 80
LINK 22 CLOSED AT TIME 80
LINK 23 CLOSED AT TIME 80

LINK 21 OPEN AT TIME 104
LINK 22 OPEN AT TIME 104
LINK 23 OPEN AT TIME 104
```

Figure 3.16. Scripts that represent the Villa Cardenas links opening at 8 am on Wednesday (time 56), closing on 8 am Thursday (time 80), and reopening on 8 am Friday (time 104).

One of our tasks was to optimize the schedule of opening and closing valves. The model communicates how long each neighborhood receives water using each combination of open valves. After testing many combinations, we created a hypothetical optimized schedule and compared the results with the current schedule. A non-optimal schedule is one that increases the period of service in one region, at the expense of another. As a baseline, an optimal schedule is one that provides service to all users for longer than is currently being provided. Ideally, our final schedule provides service to each user for an equal amount of time and at an equal flow rate.

3.6 Patacón Connection

In addition to using our EPANET model to create an optimized schedule, we evaluated the proposal for a new pipeline that we are referring to as the “Patacón Connection”. IDAAN is in the early stages of planning the Patacón Connection to fix the supply shortage issues in Corregimiento Kuna Nega. They propose building a new pump station where the main street, Hacia Villa Cardenas, meets the neighborhood of Villa Cardenas (Figure 3.17). They may also improve the Northern Valle de San Francisco Tank, which is currently nonfunctional. To bring additional water from the Patacón neighborhood, IDAAN plans to build a 16 inch ductile iron pipeline that starts at Tank Patacón and ends at Hacia Villa Cardenas at the labeled pin in Figure 3.17. IDAAN asked us to evaluate their proposal, and determine any solutions that would ensure the long term success of this new project. The strength of each pump as well as the size and material of each pipe is open to our recommendations.

Figure 3.17. How the Patacón Pump Station (Pump Station Patacón) could connect to the existing system. The red lines represent existing pipelines, the blue line is the proposal. This route takes into account IDAAN's design plans to intercept the system at the Villa Cardenas 1 Junction, mitigates extraneous altitude changes, and follows existing roads as closely as possible.

For our project, we built two sets of models: one using the Hazen-Williams Equation and one using the Darcy-Weisbach Equation (Appendix C). Although both model the Patacón Connection, there is a valve that controls whether or not the Patacón Connection is supplying water to the existing region of Corregimiento Kuna Nega. This valve is closed when we evaluate the current system, and opened when we evaluate the current system plus the Patacón Connection. We based the Patacón Connection branch on the path that IDAAN will most likely take to establish this connection (Figure 3.17). Using the same methods as described in section

3.4, we measured the Patacón tank’s volume, length of pipelines, and elevation at key points in our system. To input the volume of the Patacón tank, which holds 1,000,000 gallons or 133,680.556 ft^3 of water, into our EPANET model, we calculated a corresponding diameter of 119.097 ft to an assumed tank height of 12 ft.

We also requested the pump curve for the Patacón pump station. When the pumps at the Patacón Pump Station use a 10.35 inch impeller, they are most efficient when the flow rate is 1500 GPM (Figure 3.18). At this flow rate, the pumps increase the pressure by 240 feet of head and have an efficiency of 84.8%. Figure 3.19 illustrates the pump curve as input into the EPANET model.

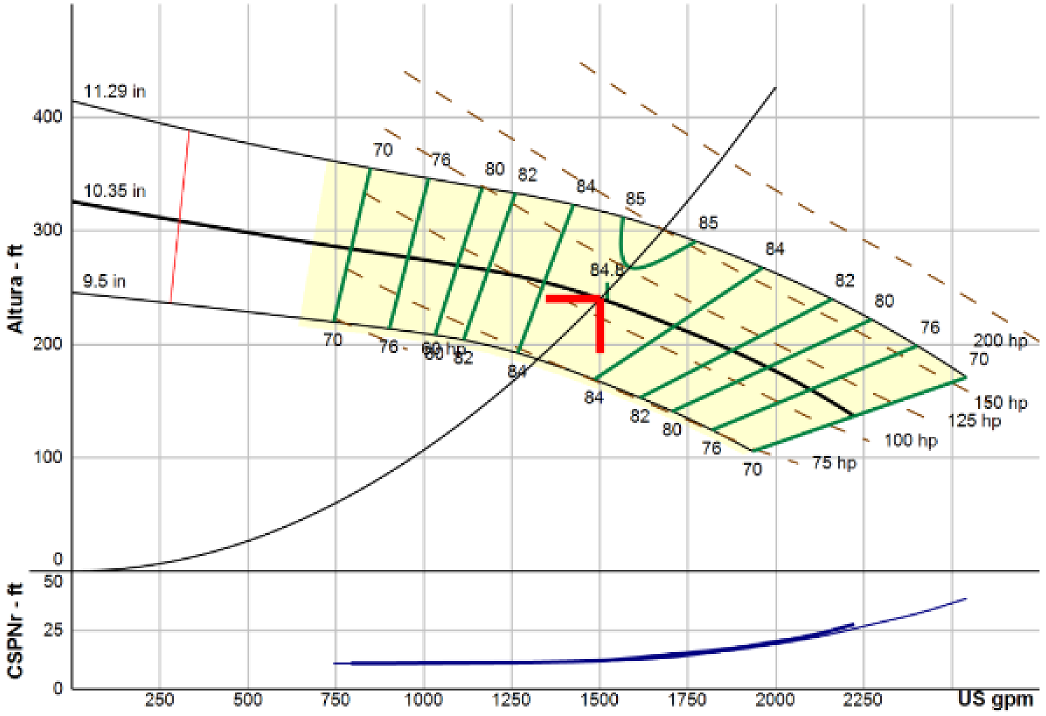
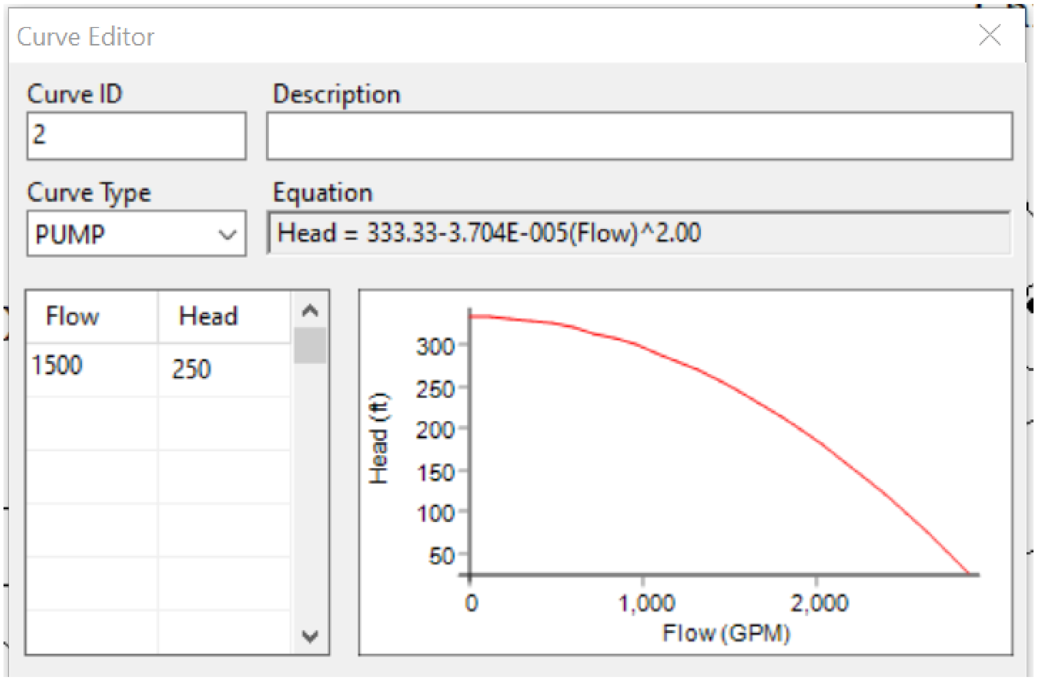


Figure 3.18. Pump Curve for the proposed Cerro Patacón Pump Station. For the full reference sheet, see Appendix B



Curve Editor

Curve ID: 2

Description:

Curve Type: PUMP

Equation: Head = 333.33-3.704E-005(Flow)^2.00

Flow	Head
1500	250

Figure 3.19. The Cerro Patacón Pump Curve as input into the EPANET model.

Chapter IV: Findings

4.1 Overview of Results Needed for EPANET HMO

Our methods led us to the following results regarding updating IDAAN's internal pipe mapping system, ArcGIS. Figure 4.1 shows how the system is fairly simple starting from the Chivo Chivo Pump Station and ending in the southern region of Valle de San Francisco. In Figure 4.2, a much more developed system of pipes is shown, and this map represents the current state of the regional development much better than the previous version. The entire neighborhoods of Kuna Nega and Genesis are now populated with their respective systems with the details of their measurements and materials detailed upon inspecting their properties menus. Some measurements and piping materials located in the Lucha Franco and Villa Cardenas regions were corrected as well.

Figure 4.1. IDAAN ArcGIS model prior to system updates made by the team.

Figure 4.2. IDAAN ArcGIS model after system updates were made by the team.

Secondly, our work generated two house counts of the region. Table 4.1 shows the data as counted by the regions outlined in Appendix B with corresponding color coding. This table shows the breakdown of the count by team members and how the data are processed to generate a value for Total Demand by region in gallons. From these estimates, we found that the population has grown since the Chivo Chivo Pump Station's construction in 2014, and in the past 3 years, the number of houses has grown by 3% per year.

House	House Count	Avg	Media	Std	% Std	Error	Total Demand

Count Regions	Bridget	Steve	Nick		n	Dev	Dev	(Count)	(Gal/day)
VC East	189	179	203	190.3	189	12	6	6.960	95,166.67
KN & Gen	828	813	795	813	816	17	2	9.644	406,500.00
VC West	370	384	346	366.7	370	19	5	11.096	183,333.33
VC South	265	225	218	236	225	25	11	14.640	118,000.00
SF South	222	190	181	197.7	190	22	11	12.441	98,833.33
SLR	818	943	805	855.3	818	76	9	43.994	427,666.67
Total	2692	2737	2548	2659	2692	99	4	57.000	1,329,500.00

Table 4.1. First house count results per the procedure outlined in Chapter 3.5.1 and data processing that resulted in Total Demand by region in gallons.

Table 4.2 contains the data from our second house count of the region. This house count provided a more accurate value for demand where leakage is taken into account, and we input the final data value directly into the EPANET model at the junction of each pipe denoted on the leftmost column of the table. Table 4.2 also contains the length of each pipe in our network, found using Google Earth, which we used in our EPANET model. Note that not all pipeline lengths are relevant in our network model, so some have been omitted from Table 4.2 below. Pipe 44 represents the Patacón Connection, where we used Google Earth to measure the proposed pipeline length from Villa Cardenas 1 to the Patacón tank.

Node	**Length (ft)**	**Houses (#)**	**Node Demand (GPM)**

Pipe 1	781	241	83.68
Pipe 3	1273	0	0.00
Pipe 4	2337	16	5.56
Pipe 5	1675	5	1.74
Pipe 6	416	11	3.82
Pipe 7	1376	225	78.13
Pipe 8	3065	58	20.14
Pipe 9	192	0	0.00
Pipe 10	1475	168	58.33
Pipe 11	1758	50	17.36
Pipe 12	559	57	19.79
Pipe 13	495	79	27.43
Pipe 14	3492	79	27.43
Pipe 15	412	12	4.17
Pipe 16	305	29	10.07
Pipe 17	332	14	4.86
Pipe 18	637	49	17.01
Pipe 19	572	18	6.25
Pipe 20	7633	37	12.85
Pipe 21	1617	52	18.06
Pipe 22	2594	142	49.31
Pipe 23	2435	402	139.58
Pipe 24	361	0	0.00
Pipe 25	559	56	19.44
Pipe 26	953	244	84.72
Pipe 28	334	88	30.56
Pipe 29	1718	213	73.96
Pipe 30	771	34	11.81
Pipe 31	410	43	14.93
Pipe 32	814	128	44.44
Pipe 34	3380	0	83.68

Pipe 35	234	0	0.00
Pipe 36	7802	0	0.00
Pipe 38	1067	0	0.00
Pipe 41	920	0	0.00
Pipe 42	3328	118	40.97
Pipe 44	12571	0	0.00
Pipe 45	1946	0	0.00
Pipe 46	746	128	44.44

Table 4.2. Second house count results per the procedure outlined in Chapter 3.5.1 and data processing that resulted in Total Demand by node in gallons per minute.

4.2 Field Data

We obtained data in the field in regard to flow rate and pressure at different points in the system, which we used to evaluate the efficacy of the proposed schedule (Table 4.3). Blank areas in the data indicate data points that cannot be taken due to either the lack of water hydrants in the area for pressure measurements or insufficient exposed piping for flow measurements. The neighborhoods of Valle de San Francisco and Santa Librada Rural are not included in Table 4.3 because of their lack of both hydrants and exposed pipelines.

Location / Node	Flow Rate (GPM)	Pressure (psi)
Tank Chivo Chivo	815.27	-
Pump Chivo Chivo	1033.53	206.34
Villa Cardenas	-	31.45
Policía	-	9.09 (Wed) ; 24.56 (Sat)
Genesis	-	27.442
Kuna Nega	90.579	-

Table 4.3. The measured flow rates and pressures at different points along the water delivery system.

Water flow in the entrance pipe to the source tank at the Chivo Chivo Pump Station averaged 815.27 GPM over the 20 minutes that we recorded. The change over time and trend of this record is shown in Figure 4.3. Although flow fluctuated over the 20 minute period, the value hovered around 800 GPM, with an average of 815.27 GPM. We measured the flow rate of the water flowing out of the tank to be 1033.53 GPM over the same 20 minute period. The exit flow in the pump station, as illustrated in Figure 4.4, fluctuates in a similar manner to that in Figure 4.3. However, because the exit pipe is horizontal, the water flows more easily than the entrance line which is vertical and flows against gravity. The difference between the flow values into and out of the tank is likely due to the valve between tanks not being completely closed. As the water pushed just past the pumps, we recorded the pressure of the water as 206.34 psi. In Figure 4.5, the value dips slightly twice during the day, but it otherwise remains constant over the 24 hour period. According to our data, this pattern is a daily occurrence.

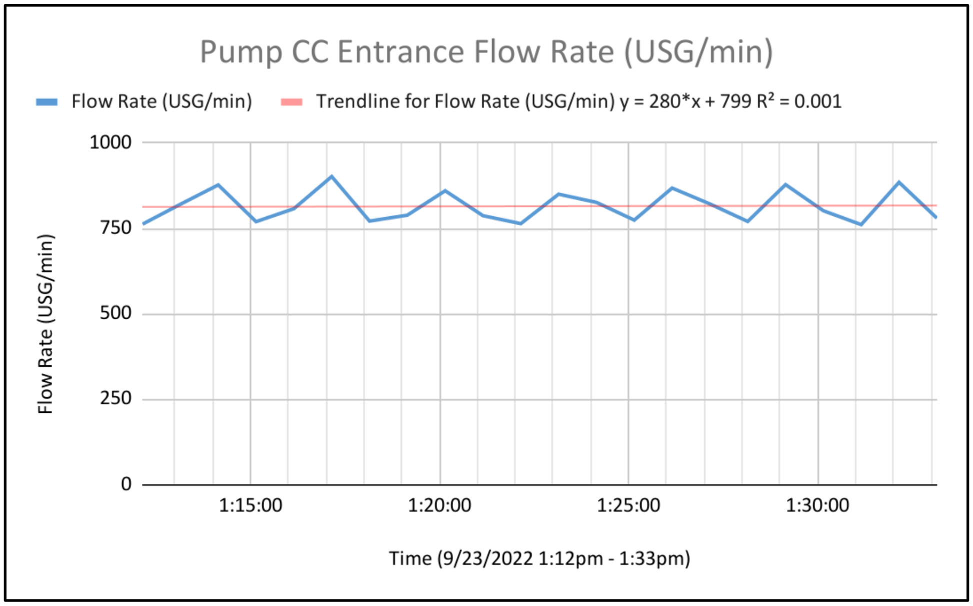


Figure 4.3. Flow rate values entering the tank at the Chivo Chivo Pump Station on September 23rd recorded over the course of 20 minutes.

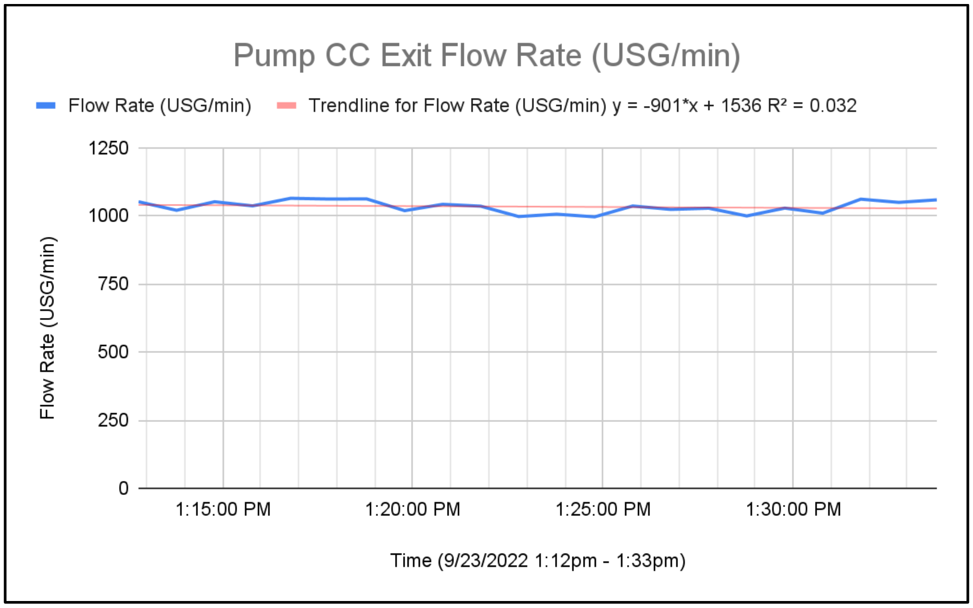


Figure 4.4. Flow rate values exiting the tank at the Chivo Chivo Pump Station on September 23rd recorded over the course of 20 minutes.

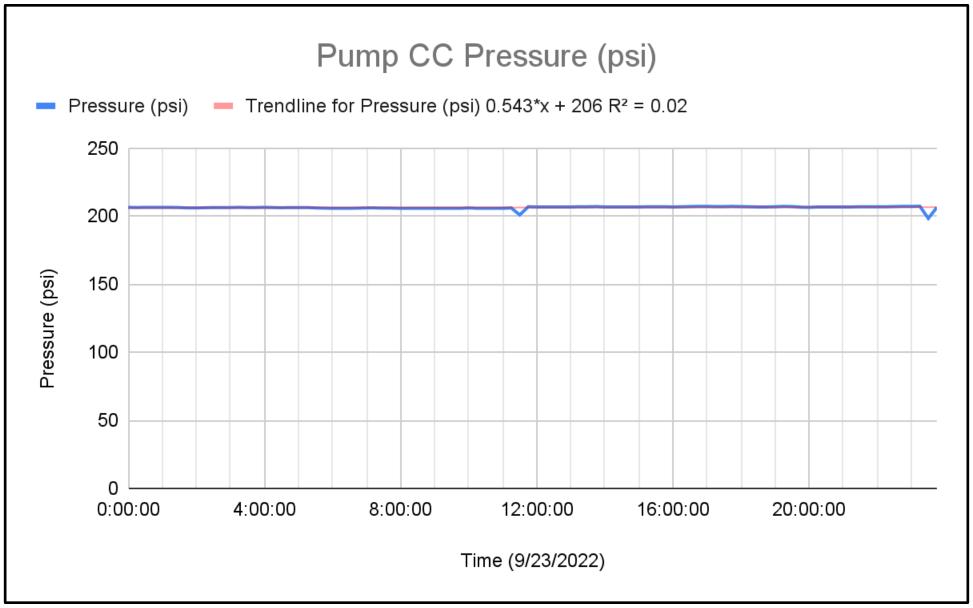


Figure 4.5. Exit pressure values at the Chivo Chivo Pump Station on September 23rd *recorded over the course of 24 hours.*

Next, we measured pressure in the Villa Cardenas region. The pressure gauge installed in Villa Cardenas at "JunVC2" showed peak pressure values in the periods of time between Wednesday to Thursday afternoons and Saturday to Sunday afternoons (Figure 4.6). This region has water supply available between Wednesday morning to Thursday morning and Saturday morning to Sunday morning. This relationship shows that peaks in the graph indicate the availability of water. The average pressure in this node during the periods of available water is 31.452 psi.

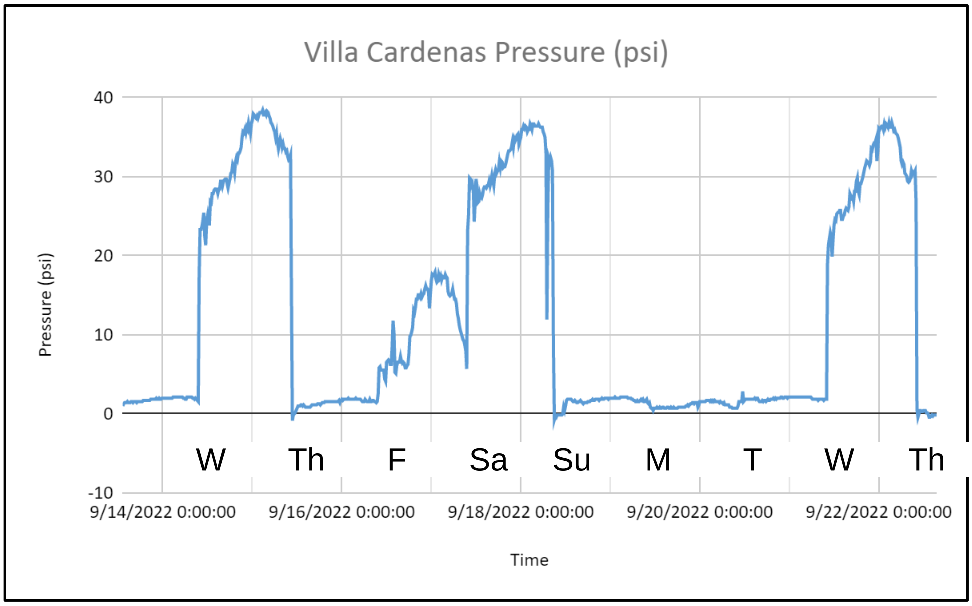


Figure 4.6. Nodal pressure at Node Jun_VC2 on September 13th recorded over the course of one week.

The next node that we analyzed was the Policía Junction at the Kuna Nega/Valle de San Francisco split. As shown in Figure 4.7, the pressure gauge displayed a wide array of values that changed at the beginning of each day over the course of the two week period (September 14th to September 27th). For this node, the minimum value in this data set is -1.138 psi, which indicates suction in the pipes, while the pressure increases to values as high as 132.382 psi.

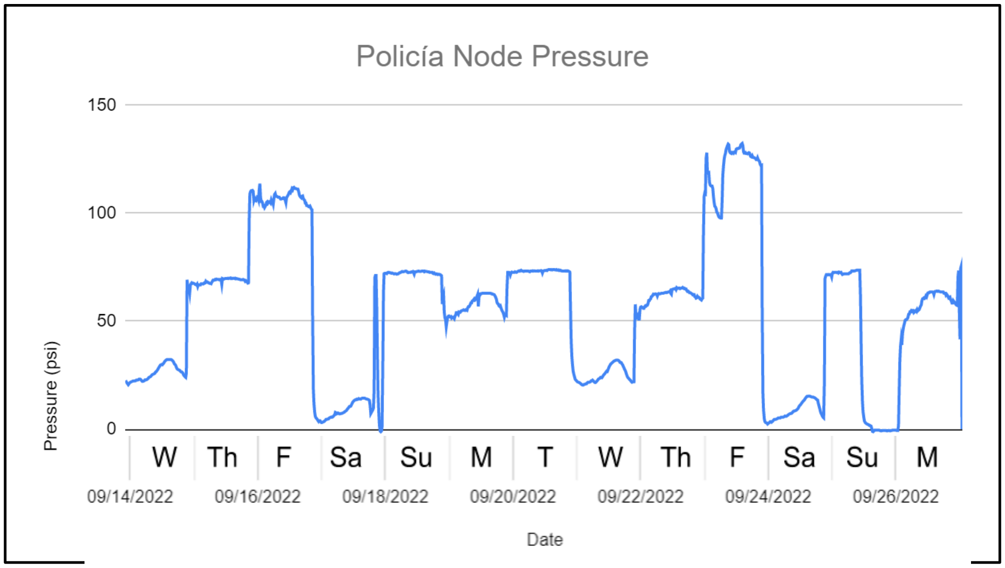


Figure 4.7. Exit pressure values at the National Police Station at the Kuna Nega/Valle de San Francisco pipe split on September 23rd recorded over the course of two weeks.

The pressure values we measured in Genesis at Junction “Gen” showed peak pressure values on Monday mornings and the period between Tuesday mornings to Wednesday afternoons (Figure 4.8). We were not given the water delivery schedule for this region, so our data on pressure peaks is our most reliable source for this information. The average pressure in at this node during the periods of available water is 27.442 psi.

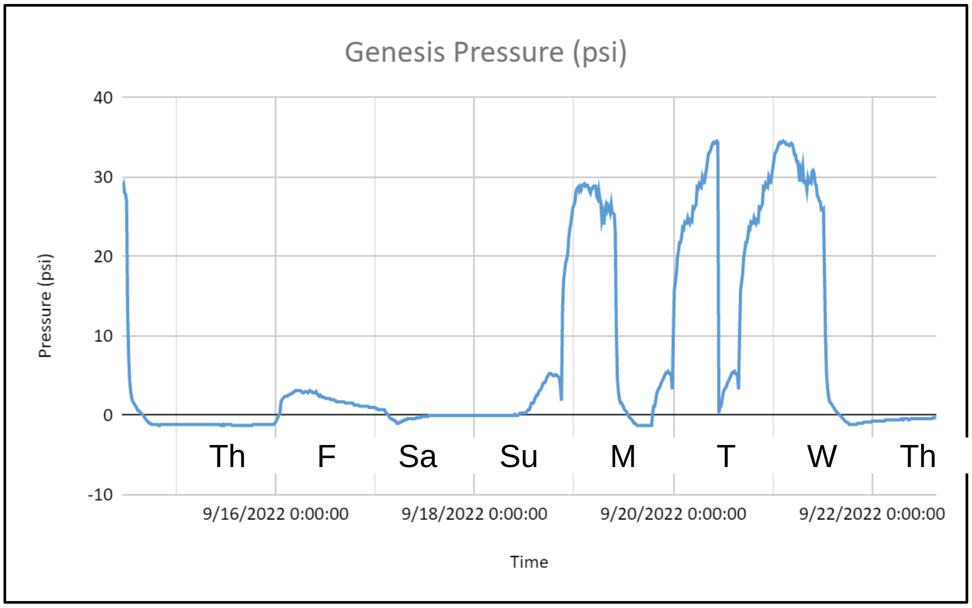


Figure 4.8. Nodal pressure in Genesis on September 15th recorded over the course of one week.

Figure 4.9 displays the rate of flow of water across the bridge in Kuna Nega. This point in the system is located along the pipe link between the junction nodes of “JunKNBeforeBridge” and “JunKNAfterBridge”. We recorded this measurement over a period of 14 minutes with an average output of 98.579 USG/min. This data indicates a 90.46% decrease in flow rate from the pump station to Kuna Nega.

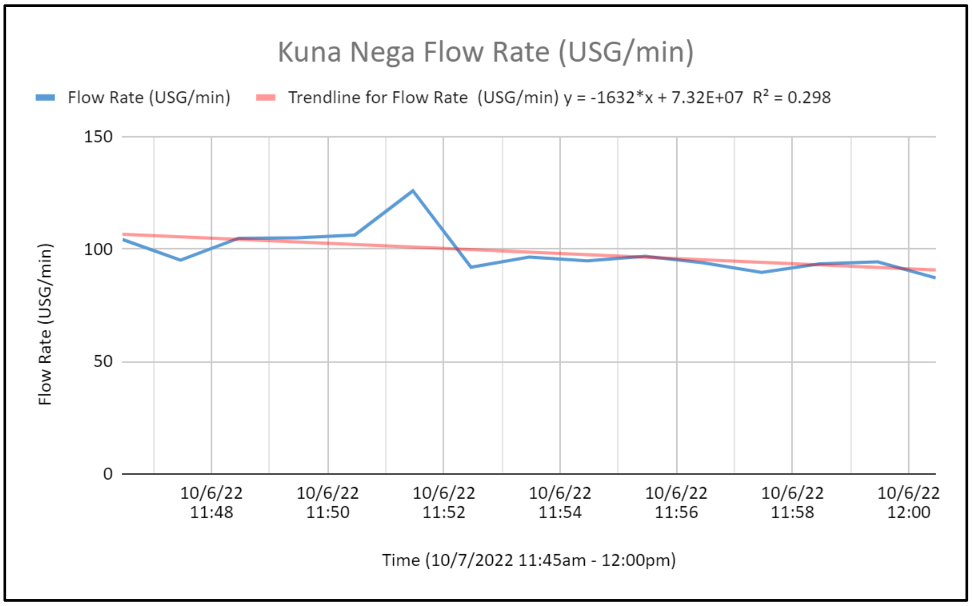


Figure 4.9. Nodal Flow Rate in Kuna Nega at “Junction JunKNBeforeBridge” on October 6th recorded for a period of 14 minutes.

Next, we measured elevations of the most important points in our network, at pumps, tanks, and junctions (Table 4.4). All measurements had a precision of 4.5 feet or less.

Category	Location	Elevation (ft)	Precision (ft)
Pumps	Chivo Chivo	389	4.5
	Valle de San Francisco	232.1	2.4
	Patacón	231	3
Tanks	Santa Librada Rural	667.4	2.3
	Kuna Nega (La Paz)	407.3	2.3
	Valle de San Francisco Norte	337	4.1
	Valle de San Francisco Sur	431.4	2.6
	Genesis	379.6	2.2
	Patacón	453.9	3.5
Junctions	Proposed Pump	402.9	1.7
	Villa Cardenas 1	623.9	2.3
	Policia	283.1	1.9

Table 4.4. The elevation of important tanks, pumps, and important junctions in our network.

4.3 EPANET HMO Results

Once we input all the previously mentioned data into EPANET, we produced two versions of our models. The first model provided below represents the existing network with the Hazen WIlliams Equation (Figure 4.10). Running the model with the Hazen-Williams Equation and Darcy-Weisbach Equations gave us almost identical results.

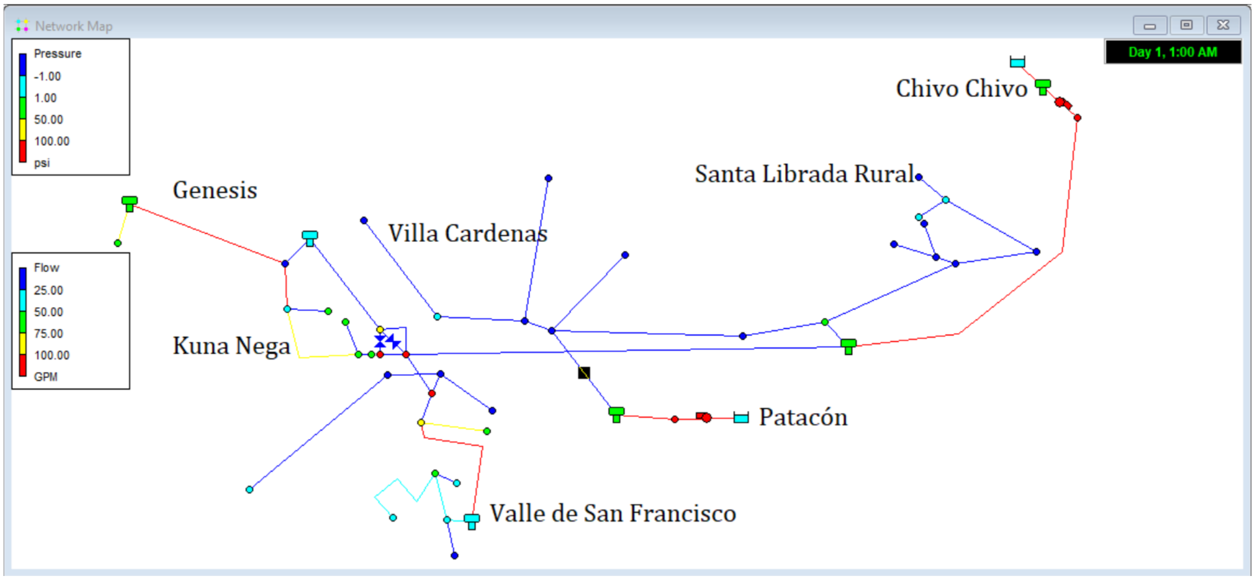


*Figure 4.10. Window capture of the final Hazen-Williams EPANET model used to simulate the different delivery schedules **without** the Patacón Connection design implemented on **Day 1 at 1 AM**.*

Next, we produced a model to represent the existing network plus the Patacón Connection. Figure 4.11 represents the existing network plus the Patacón Connection using the Hazen-Williams equation.

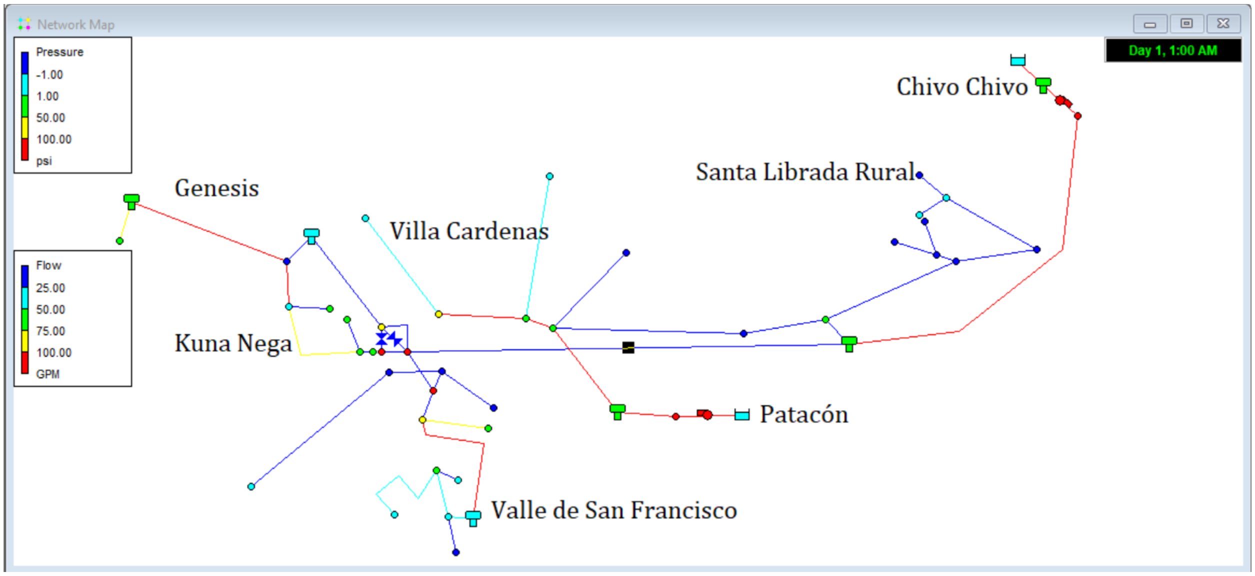


Figure 4.11. Window capture of the final Hazen-Williams EPANET model used to simulate the different delivery schedules ***with*** *the Patacón Connection design implemented on* ***Day 1, 1 AM****.*

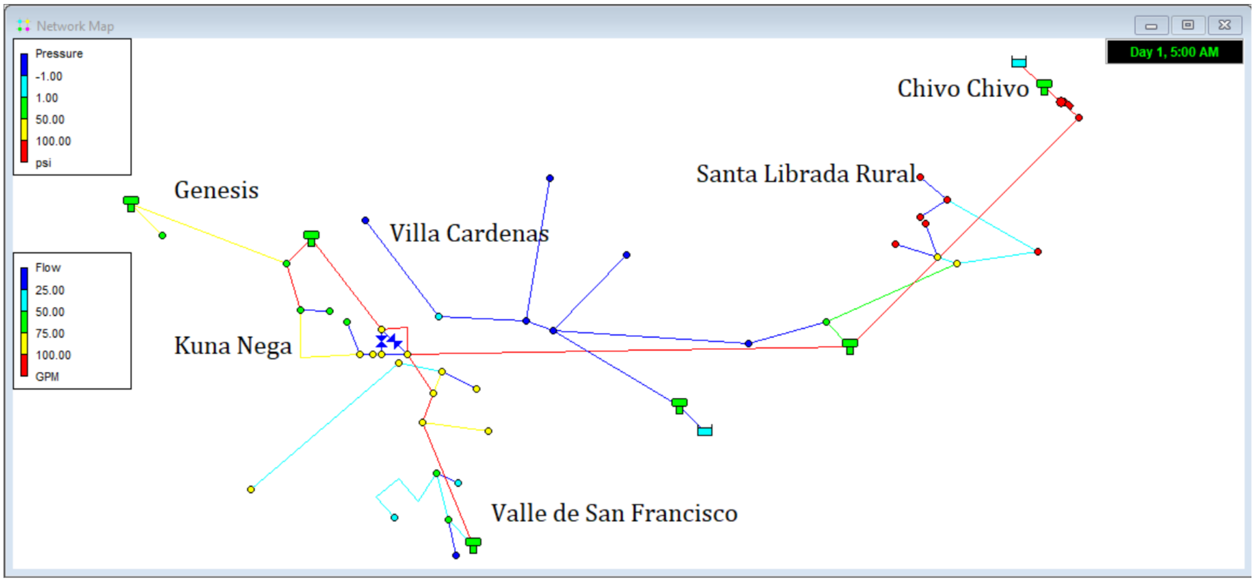


Figure 4.12. Window capture of the final Hazen-Williams EPANET model used to simulate the different delivery schedules ***without*** *the Patacón Connection design implemented on* ***Day 1 at 5 AM****.*

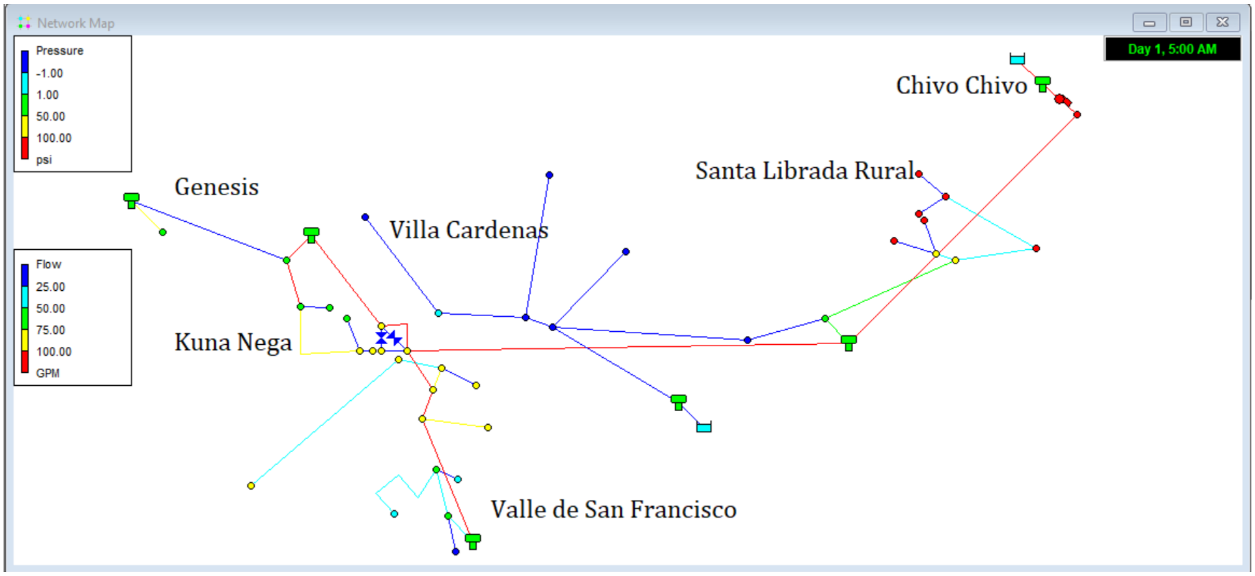


Figure 4.13. Window capture of the final Darcy-Weisbach EPANET model used to simulate the different delivery schedules ***with*** *the Patacón Connection design implemented on* ***Day 1 at 5 AM****.*

As can be seen in Figures 4.12 and 4.13, there is little difference in output between the models using the Hazen-Williams and Darcy-Weisbach equations. This difference produces an insignificant effect on the results. Therefore, in our conclusion, we chose to interpret the data from the Hazen-Williams equation.

4.4 Limitations

The findings of a model are only as good as the quality of the data collected. Put garbage in, you get garbage out. While building our models, we endeavored to use exact numbers, but it is impracticable to know the precise values for each model input. The network demand and roughness coefficients we fed the model are estimations.

Our calculations of demand were based on established estimates given to us by IDAAN (Appendix B). We estimated that there were 5 people per house, and that each person used 100 gallons of water per day, which totals to 500 gallons per house per day. Although IDAAN believes these estimates are accurate, we know that our results are only as accurate as these values. If more people live in each house, or if consumption rates are higher, then demand values are too low, and not enough water will reach each house. While houses closest to tanks would get enough water, houses farther away would be irregularly supplied. If we underestimated demand, pressures would be higher than modeled which could pose an inconvenience when water exits faucets at high pressure, and leakage would increase. As a worst-case scenario, pressures could rise so high that pipes could burst.

Applying the same roughness coefficients for the entire system is another limitation to our model. We drew our roughness coefficients from tables that assume the pipes are new. As pipes age, the inner wall of the pipe degrades (Figure 4.14). This internal corrosion increases the amount of friction that the water experiences as it travels along pipe walls.

Figure 4.14. An example of a corroded cast iron pipe ("Corroded Cast Iron Pipe," n.d.).

Since the newest pipes in our network are 15 years old, the roughness coefficients we used could be outdated. In the Hazen-Williams equation, we likely used too large coefficients, which could result in an underestimation of pressure loss due to friction. If we undervalued friction, then the true pressure in the pipes would be lower than what we modeled. Houses at high elevations would therefore not get enough water unless pumps were made stronger. Darcy-Weisbach coefficients are the opposite: too small coefficients underestimate friction and too large coefficients overestimate friction. Since the pipes across our network vary in age and material, each pipe would need a unique roughness coefficient to accurately estimate friction. While we could determine roughness experimentally, by conducting tests on parts of each pipe, it is an expensive and lengthy process. Despite these limitations, it should be noted that ductile and cast iron pipes are most affected by corrosion. Since most of the pipes in our network are made of PVC, this limitation is not as significant as it could be.

There were also numerous limitations to our project because we could not collect all the data that we had hoped we would. Such data include leakage estimates, more elevations, more flow and pressure values along our system, and the Genesis pipeline layout.

After researching various methods to estimate leakage, as seen in section 3.5.2, we ultimately decided not to pursue estimating leakage in our network. Although we planned on incorporating leakage into our model to make it as accurate as possible, we did not have enough time or resources to measure it during the course of our project. Instead, we assumed that there was no leakage in our system. Although we suspect leakage is the reason why the Santa Librada tank is empty and our no leakage assumption could contribute to model errors, IDAAN assured us that their standard estimate of 100 gallons per day per person is an overestimation. This estimate is artificially high to account for leakage occurring throughout the system. This built in safety factor may mean that assuming no leakage in our model is not as detrimental as it may seem.

As previously mentioned, we measured elevation for approximately half of the system's components in the field. The other half were estimated using Google Earth, which could result in slightly inaccurate elevations at these points. For the Genesis tank, which is lifted off the ground, we estimated its height above ground level. These inaccuracies, if large enough, could result in skewed flow and pressure values, but the scale of these estimates will not affect our outcomes to a great degree. Additionally, the altimeter we used measured elevation in ellipsoid height, not orthometric height. Ellipsoidal elevation assumes that the Earth is a perfect ellipsoid, and this assumption is sufficient when comparing elevations within an area of a few miles, like in our project. All of our elevations had a precision of 4.5 feet or less, so errors due to imprecise elevation measures amount to 2 psi or less.

We were unable to measure all the flow and pressure values throughout our network (Table 4.3). As previously mentioned in section 3.4, we could not obtain a strong enough flow signal at the Santa Librada tank to observe any reading. Since there was no hydrant in this location, we could not measure pressure either. Similarly, the Valle de San Francisco tank is also nonfunctional at the moment, and we could not measure pressure or flow rates for this location. The lack of these data points meant that we were unable to compare our simulation data to the current values of flow and pressure. This limitation inhibited our ability to make more meaningful conclusions about the functions of these locations and perfectly illustrates why these data are necessary. For the remaining data we planned to collect, the pipelines at these locations did not have enough exposed pipe length to allow for proper measurements, and it was uneconomical to excavate these pipes. This void in our comparative data has the same negative and positive limitations as the lack of tank data previously mentioned.

In addition to not collecting all the data that we wanted to, we would have also liked to collect our data over longer periods of time. Due to the rotational schedule, flow is different on different days, so we would have preferred measurements from every day of the week. Nevertheless, our model functions well, as the outputs of our model closely match the pressure and flow rate data we collected. The points of error due to corrosion and elevation had a minimal effect on our outcomes and conclusions. The inability to measure current flow and pressure values at a handful of locations also does not affect the accuracy of our model since we only used these values to compare against our model, and they were not integral to the generation of the model itself. We generated our optimized schedule despite these limitations, and we used the data that were available to prove that our changes had a positive effect on delivery equity.

Chapter V: Conclusions & Recommendations

5.1 Immediate Recommendations

There are two reasons why water might not reach someone's faucet. Either there is insufficient pressure or flow. Pumps increase the pressure of water, and friction from narrow pipes decreases pressure. Pressure decreases as water travels uphill and increases downhill. Water pressure should be at least 20 psi at faucets, ideally 50 psi. If pressure is too low, pumps must be added or pipes widened. Other times, flow is too low. When the demand for water exceeds the amount of water coming into the network, more water should enter the system. If there are leaks, fixing them can also fix the flow shortage.

We measured 1030 gallons per minute leaving Chivo Chivo Pump Station. Water is pumped directly to Santa Librada Rural Tank, meaning 1030 gallons per minute should enter the tank. We estimated that the demand of all houses supplied by the tank was 913 ± 20 gallons. This estimation means, at most, 913 ± 20 gallons of water should leave the tank. More water enters the tank than leaves, so the water level in the tank should rise over time. Yet the tank remains empty or nearly empty. We believe the key to improving the system lies in resolving this discrepancy. We propose five possible reasons why this tank remains empty.

If water does not reach every house because pressure is too low, the amount of water leaving the network is less than demand, and the tank's water level should rise even faster. Perhaps people use less water every week because of the rotational system. Again, if this is true, less water leaves than expected, so net flow into the tank is higher.

We proposed five reasons why net flow into Santa Librada Rural Tank might be less than we calculated, from least to most likely:

1. There has been an error measuring flow rate out of the Chivo Chivo pump station. Faulty equipment or bad measurement processes could result in incorrect measurements. One piece of evidence supporting this possibility is the discrepancy between flow into and out of the Chivo Chivo Pump. We measured inflow and exit flow to be 800 gallons per minute and 1000 gallons per minute, respectively, when they should have been equal. Although the head and flow rate listed on the label of the Chivo Chivo pump is consistent with the flow rate and pressure we measured, the pump curves are not. However, we believe this scenario is unlikely because the equipment has generated consistent results.
    a. This hypothesis can be tested by equipment anywhere flow rate or pressure is known. If the equipment is indeed faulty, IDAAN should remeasure flow rate and pressure from the exit of the Chivo Chivo Pump. Then, they should update the pump curve for the model.
2. Unauthorized connections to the network exist to places outside Corregimiento Kuna Nega. For example, unauthorized connections to Lucha Franco could exist. Lucha Franco was outside our area of study. Even if the demand-per-house estimate for our study area was correct, the network might be supplying a larger area than we realize. The demand of this larger area may be greater than the flow into Santa Librada Rural Tank.
    a. A search for unauthorized connections, especially between Villa Cardenas and Lucha Franco, could reveal whether this hypothesis is true. If the system is supplying about 300 houses outside our study area without IDAAN's awareness, it would explain the discrepancy.
3. Leakage is high. We observed leaks throughout the network. One leak at Santa Librada Rural Tank did not appear until we closed the valve on a pipe leading to the tank. Though only a flow of 1.4 gallons per minute leaked there, the tank may have other leaks.

Perhaps it leaks directly into the ground only once the water level reaches a certain height, a phenomenon that would explain why the tank's level remains low even though water flowing in exceeds water flowing out.

   a. A more thorough investigation of leakage would determine whether this hypothesis is correct. If present, large scale leakage from the Santa Librada Rural tank should be visible above ground nearby. IDAAN could also use acoustic devices to detect leaks, both at the tank and throughout the network. If high leakage is crippling the system, we recommend the leaking tank and pipes be repaired, which could eliminate the need for a rotational system.

4. Demand estimates are too low. Our estimates assumed that there are 5 people living in each house and each person needs 100 gallons per day. Either metric may be inaccurate; Corregimiento Kuna Nega does not have the same demographics as other parts of Panama, so any estimate that is applied to all of Panama may be wrong for this region. Specifically, it is likely that more than 5 people live in each house.
   a. If true demand is greater than 1030 gallons per day, then to meet demand, IDAAN would need to construct a supplementary pipe from a different source to support the system. We observed that some residents of Kuna Nega are storing water on an individual basis. Even residents who receive water only one day per week may collect multiple days worth of water on that day to store in tanks. Therefore, it is likely that the rotational system does not decrease weekly demand.
5. The pipe leading from the Chivo Chivo Pump Station to the Santa Librada Rural tank splits; because there is a junction, some water goes to the adjacent Chivo Chivo neighborhood. Therefore, less than the measured 1030 gallons of water enters Santa Librada Rural tank per minute.

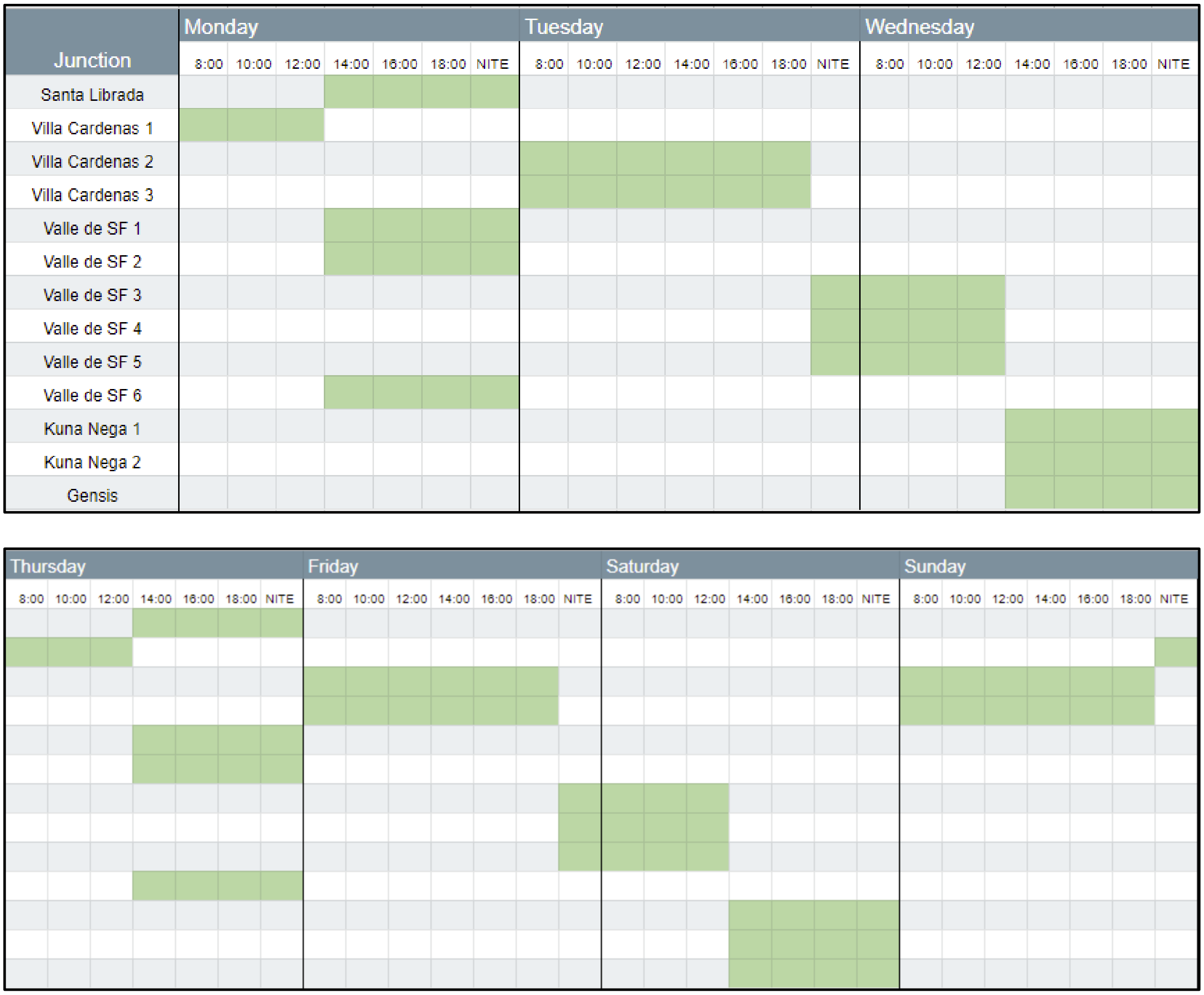
a. If this hypothesis is true, and a valve connecting the Chivo Chivo Pump Station and Chivo Chivo is shut, it should be possible to supply all of Corregimiento Kuna Nega with a continuous, seven day supply of water (though not a 24 hour supply) by improving the Chivo Chivo neighborhood's supply. One such improvement could be improving upstream pump stations. By making supply to Chivo Chivo independent of the Chivo Chivo Pump Station, the pumps can send all 1030 gallons per minute to the Santa Librada Rural Tank, which is more than enough to fill demand for all of Corregimiento Kuna Nega (913 gallons per minute), assuming our demand estimate is accurate. This project requires a study of Chivo Chivo that would ensure all of Chivo Chivo is supplied without Pump Station Chivo Chivo. Although it may require building new pumps or larger pipes in the area, it would remove the need for a supplemental pipeline from Patacón.

Throughout our project, a lack of accurate records continually hampered our progress. The accuracy of our model is limited by the accuracy of information about connections between pipes. Our nuanced recommendations reflect uncertainty about the existing network. We recommend that IDAAN requires companies to give information about new pipelines constructed, and that engineers then immediately enter this data into an electronic database, such as ArcGIS. Although unauthorized connections would go unrecorded, this database would make the process of maintaining, modeling, and improving existing infrastructure much easier.

In addition, we believe that IDAAN should reduce pressure loss in Northern Villa Cardenas. The 2" pipes connecting to roads to the North of Hacia Villa Cardenas were too narrow. IDAAN should prioritize replacing them with larger lines. In many places, more water pressure is lost due to friction than elevation. Doubling the diameter of a pipe reduces the pressure loss due to friction by a factor of 29, so even a small diameter increase would significantly improve supply problems.

5.2 Proposed Water Delivery Schedule

Throughout the process of conducting research, gathering data, and investigating the current state of the hydraulic water delivery system in place in Corregimiento Kuna Nega, our team's ultimate goal has been to solve the water crisis facing this region with an optimized water delivery schedule. Although other solutions, such as installing more transformers at certain pump stations and constructing more pump stations, would clearly solve the problem, we understood that we had to be cognizant of the limitations of a government budget. After running simulations in our model, we gained the following insights into our final delivery schedule. We propose that IDAAN implements the following schedule, in Table 5.1, in Corregimiento Kuna Nega as a method of optimizing water distribution to the homes in the region:



Junction	Monday							Tuesday							Wednesday						
	8:00	10:00	12:00	14:00	16:00	18:00	NITE	8:00	10:00	12:00	14:00	16:00	18:00	NITE	8:00	10:00	12:00	14:00	16:00	18:00	NITE
Santa Librada				🟩	🟩	🟩	🟩														
Villa Cardenas 1	🟩	🟩	🟩																		
Villa Cardenas 2								🟩	🟩	🟩	🟩	🟩	🟩								
Villa Cardenas 3								🟩	🟩	🟩	🟩	🟩	🟩								
Valle de SF 1				🟩	🟩	🟩	🟩														
Valle de SF 2				🟩	🟩	🟩	🟩														
Valle de SF 3														🟩	🟩	🟩	🟩				
Valle de SF 4														🟩	🟩	🟩	🟩				
Valle de SF 5														🟩	🟩	🟩	🟩				
Valle de SF 6				🟩	🟩	🟩	🟩														
Kuna Nega 1																		🟩	🟩	🟩	🟩
Kuna Nega 2																		🟩	🟩	🟩	🟩
Gensis																		🟩	🟩	🟩	🟩

Thursday							Friday							Saturday							Sunday						
8:00	10:00	12:00	14:00	16:00	18:00	NITE	8:00	10:00	12:00	14:00	16:00	18:00	NITE	8:00	10:00	12:00	14:00	16:00	18:00	NITE	8:00	10:00	12:00	14:00	16:00	18:00	NITE
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Table 5.1. The proposed water delivery schedule, broken down into 2-hour increments. Boxes highlighted in green indicate that the specified area receives water during that period of time.

Based on the Hazen-Williams Equation, this schedule provides equal water access per person instead of per region. It divides the day into 2-hour blocks. The last column of time in each day represents a 12-hour nighttime period (8pm to 8am). It also assumes that the Patacón connection is not built. The schedule splits Villa Cardenas into two regions (one with VC1 and the other with VC2 and VC3). It also splits Valle de San Francisco into two regions (One with VSF 1, 2, and 6, and the other with VSF 3, 4, and 5). We also propose that water supply could be suspended on certain nights of the week in an attempt to give tanks the opportunity to fill up during this time.

5.3 Recommendations for IDAAN

As we investigated the current state of the water delivery system, we considered the existing resources IDAAN has to offer to construct a realistic and cost-effective solution while aiming to meet the needs of the city and requests of IDAAN. We concluded that the agency would benefit greatly from the use of performance-based contracts in each of its new projects. We believe this change could result in the same improvements as it did in Colón. However, we recommend that the agency takes this approach for all existing projects, not just for new projects. Regular maintenance is a key component for keeping water delivery consistent and running smoothly. A performance based contract that evaluates which infrastructure needs maintenance would greatly benefit the agency.

More than any other statistic, an investigation of leakage is the best opportunity for future research with IDAAN. Leakage could be measured at tanks, at pump stations, and in the field along pipes. To improve its network, IDAAN must identify pipes and pipe laying processes that minimize leakage. If the agency had a working model for each water network, and communicated with the local community on a regular basis about how often they are getting water and at what pressure, they could more easily identify leaks. This method would result in a more efficient system which eventually minimizes water loss, because the agency would identify and fix them as they occur.

Of course, these recommendations come at a cost. Since IDAAN is a government agency, their abilities to take on new projects and reorganize resources within the agency depend on the authority of government officials. More funding, specifically allocated to the maintenance of the water networking system, would go a long way to improve the current conditions in the regions outside of Panama City.

5.4 Recommendations to Improve the HMO

Noting the limitations of the accuracy and age of Google Earth imaging data we expressed in our methods, our recommendation would be to go into the neighborhood in-person and determine population manually, similar to a census. This method would result in a more accurate count of the number of people. Since COVID-19 delayed the most recent census, we recommend adjusting our model with 2022 census data. However, that process itself would likely take longer than our project duration to accomplish all of our tasks. We also recommend collecting regular census data such as population demographics (minorities, indigenous populations, immigrants, etc) and factors including medium income as it will help to capture the situation fully. This task could likely be completed by a future IQP team, and the scope could range from technical aspects such as charting demographic changes since the last census to social aspects including gathering data on the community’s attitude toward variable water supply, IDAAN as an institution, and the Panamanian government as a whole.

As mentioned above, having a proper estimation of leakage throughout the system would greatly help our model. Knowing how much water is lost as it travels throughout the system would provide a better idea of what is going on in the overall system.

5.5 Recommendations for the Patacón Connection

We recommend that IDAAN does not further their plans with the Patacón Connection until they understand why Santa Librada Rural Tank is empty. Our model suggests that water shortages in Corregimiento Kuna Nega are a problem of pressure, not of flow, so enlarging the pipes, building stronger pumps, or supplying existing pump stations with more electrical power should remedy the problem, especially in Villa Cardenas. Therefore, a new line should not be built from Patacón to supply Corregimiento Kuna Nega.

Over the past seven years, a design error has cost the people of Kuna Nega years of water. With the help of IDAAN, we went into the field to gather information about the water supply network. We built a hydraulic model to simulate the flow of water so we could understand the network's problems firsthand. Finally, we proposed a series of recommendations to improve the water network. In short, we used engineering principles to reverse the error and hopefully improve the lives of thousands of Panamanians.

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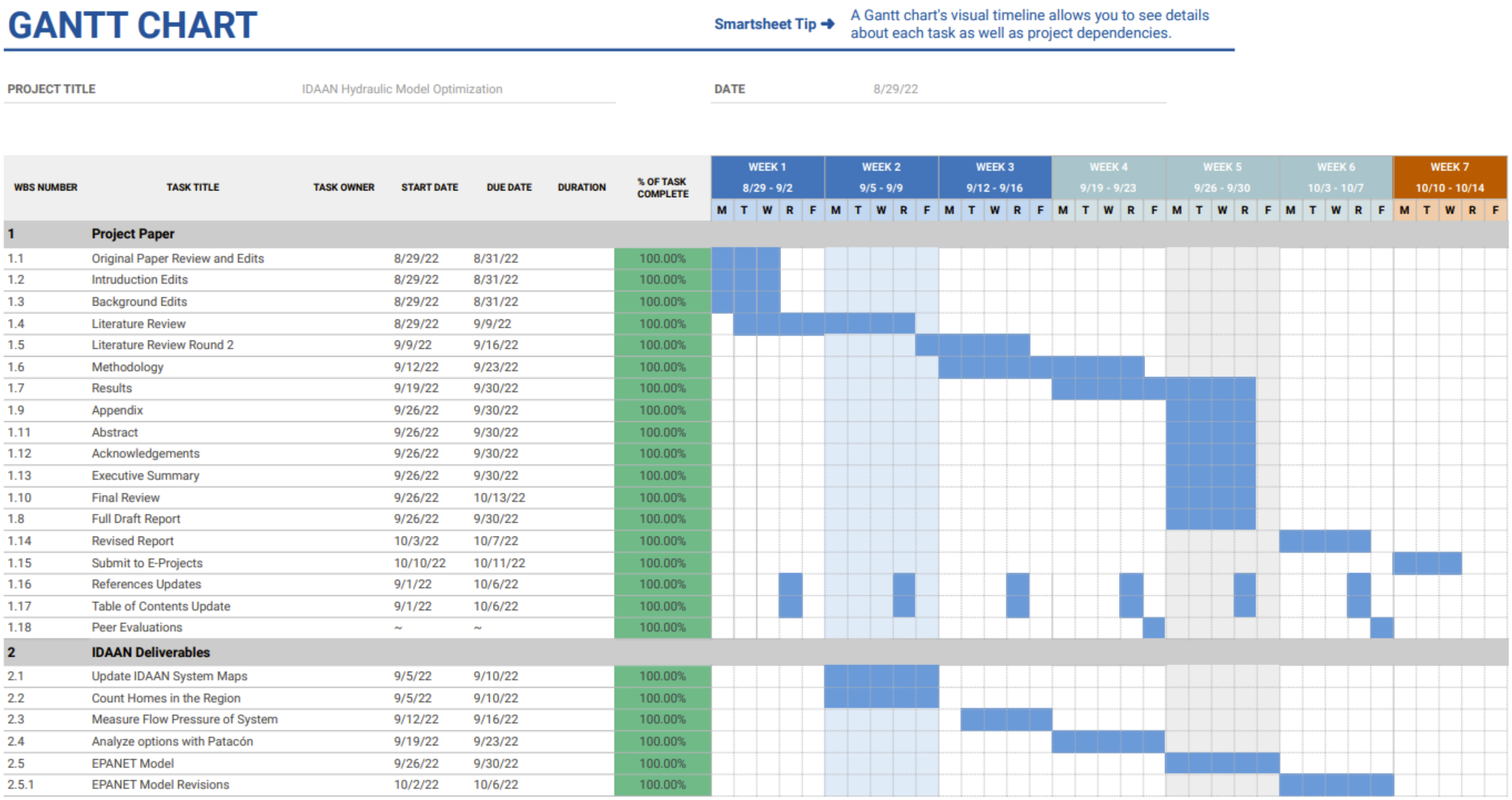
Appendix A: Project Schedule



GANTT CHART

Smartsheet Tip ➜ A Gantt chart's visual timeline allows you to see details about each task as well as project dependencies.

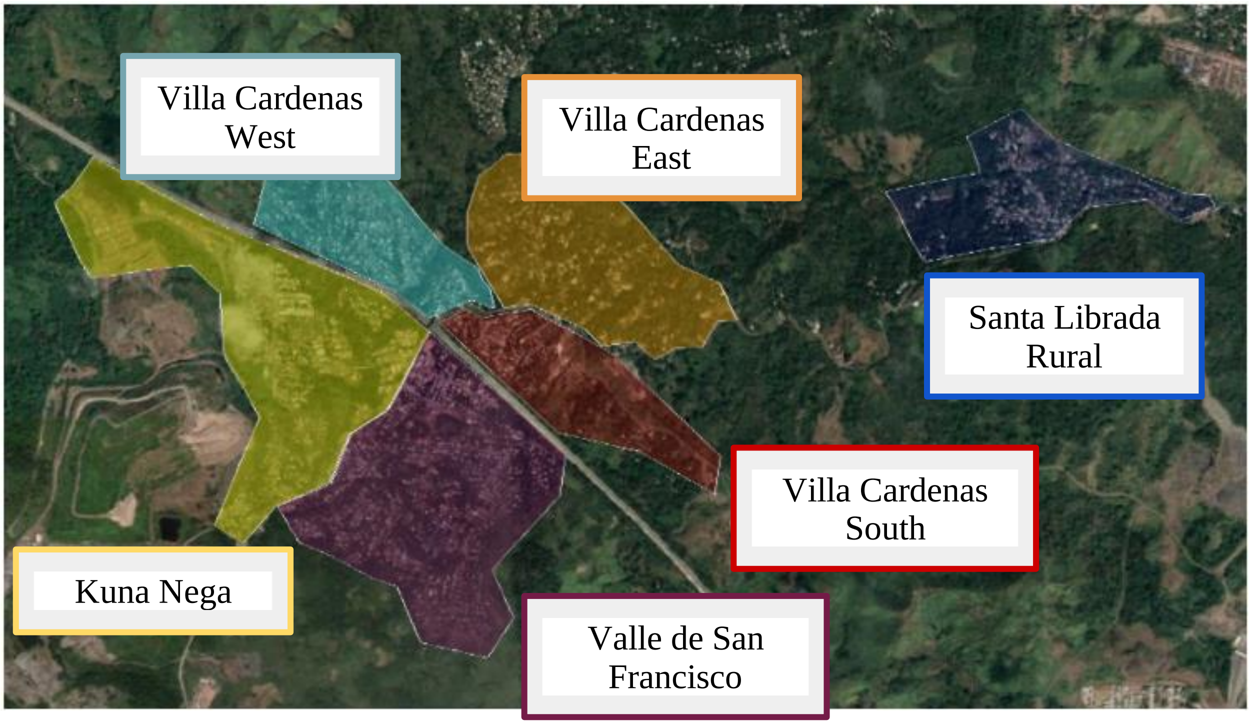
PROJECT TITLE IDAAN Hydraulic Model Optimization

DATE 8/29/22

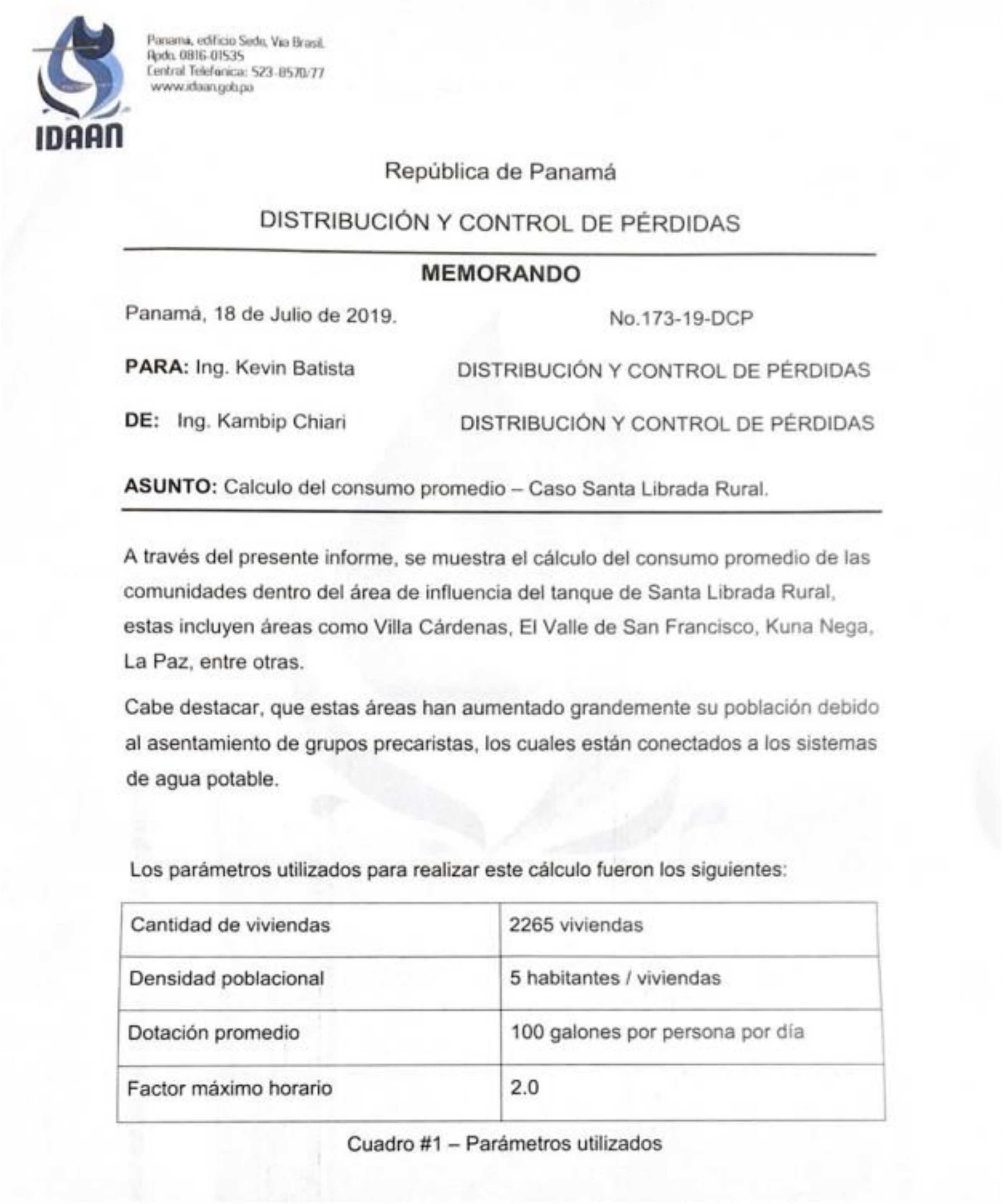
WBS NUMBER	TASK TITLE	TASK OWNER	START DATE	DUE DATE	DURATION	% OF TASK COMPLETE
1	**Project Paper**					
1.1	Original Paper Review and Edits		8/29/22	8/31/22		100.00%
1.2	Intruduction Edits		8/29/22	8/31/22		100.00%
1.3	Background Edits		8/29/22	8/31/22		100.00%
1.4	Literature Review		8/29/22	9/9/22		100.00%
1.5	Literature Review Round 2		9/9/22	9/16/22		100.00%
1.6	Methodology		9/12/22	9/23/22		100.00%
1.7	Results		9/19/22	9/30/22		100.00%
1.9	Appendix		9/26/22	9/30/22		100.00%
1.11	Abstract		9/26/22	9/30/22		100.00%
1.12	Acknowledgements		9/26/22	9/30/22		100.00%
1.13	Executive Summary		9/26/22	9/30/22		100.00%
1.10	Final Review		9/26/22	10/13/22		100.00%
1.8	Full Draft Report		9/26/22	9/30/22		100.00%
1.14	Revised Report		10/3/22	10/7/22		100.00%
1.15	Submit to E-Projects		10/10/22	10/11/22		100.00%
1.16	References Updates		9/1/22	10/6/22		100.00%
1.17	Table of Contents Update		9/1/22	10/6/22		100.00%
1.18	Peer Evaluations		~	~		100.00%
2	**IDAAN Deliverables**					
2.1	Update IDAAN System Maps		9/5/22	9/10/22		100.00%
2.2	Count Homes in the Region		9/5/22	9/10/22		100.00%
2.3	Measure Flow Pressure of System		9/12/22	9/16/22		100.00%
2.4	Analyze options with Patacón		9/19/22	9/23/22		100.00%
2.5	EPANET Model		9/26/22	9/30/22		100.00%
2.5.1	EPANET Model Revisions		10/2/22	10/6/22		100.00%

Appendix B: Reference Pictures

Corregimiento Kuna Nega Map



IDAAN’s 2019 Distribution Report in Corregimiento Kuna Nega



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República de Panamá

DISTRIBUCIÓN Y CONTROL DE PÉRDIDAS

MEMORANDO

Panamá, 18 de Julio de 2019. No.173-19-DCP

PARA: Ing. Kevin Batista DISTRIBUCIÓN Y CONTROL DE PÉRDIDAS

DE: Ing. Kambip Chiari DISTRIBUCIÓN Y CONTROL DE PÉRDIDAS

ASUNTO: Calculo del consumo promedio – Caso Santa Librada Rural.

A través del presente informe, se muestra el cálculo del consumo promedio de las comunidades dentro del área de influencia del tanque de Santa Librada Rural, estas incluyen áreas como Villa Cárdenas, El Valle de San Francisco, Kuna Nega, La Paz, entre otras.

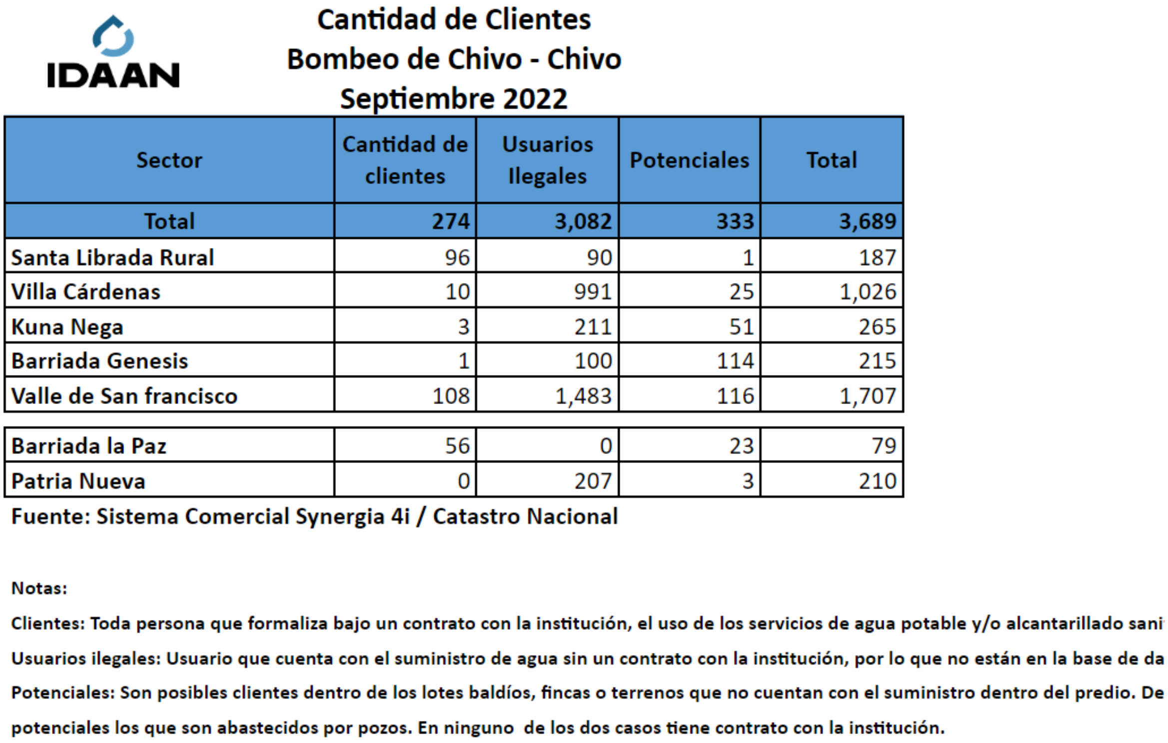
Cabe destacar, que estas áreas han aumentado grandemente su población debido al asentamiento de grupos precaristas, los cuales están conectados a los sistemas de agua potable.

Los parámetros utilizados para realizar este cálculo fueron los siguientes:

Cantidad de viviendas	2265 viviendas
Densidad poblacional	5 habitantes / viviendas
Dotación promedio	100 galones por persona por día
Factor máximo horario	2.0

Cuadro #1 – Parámetros utilizados

IDAAN’s September 2022 Chivo Chivo Pump Station Customers Record



IDAAN

Cantidad de Clientes
Bombeo de Chivo - Chivo
Septiembre 2022

Sector	Cantidad de clientes	Usuarios Ilegales	Potenciales	Total
Total	**274**	**3,082**	**333**	**3,689**
Santa Librada Rural	96	90	1	187
Villa Cárdenas	10	991	25	1,026
Kuna Nega	3	211	51	265
Barriada Genesis	1	100	114	215
Valle de San francisco	108	1,483	116	1,707
Barriada la Paz	56	0	23	79
Patria Nueva	0	207	3	210

Fuente: Sistema Comercial Synergia 4i / Catastro Nacional

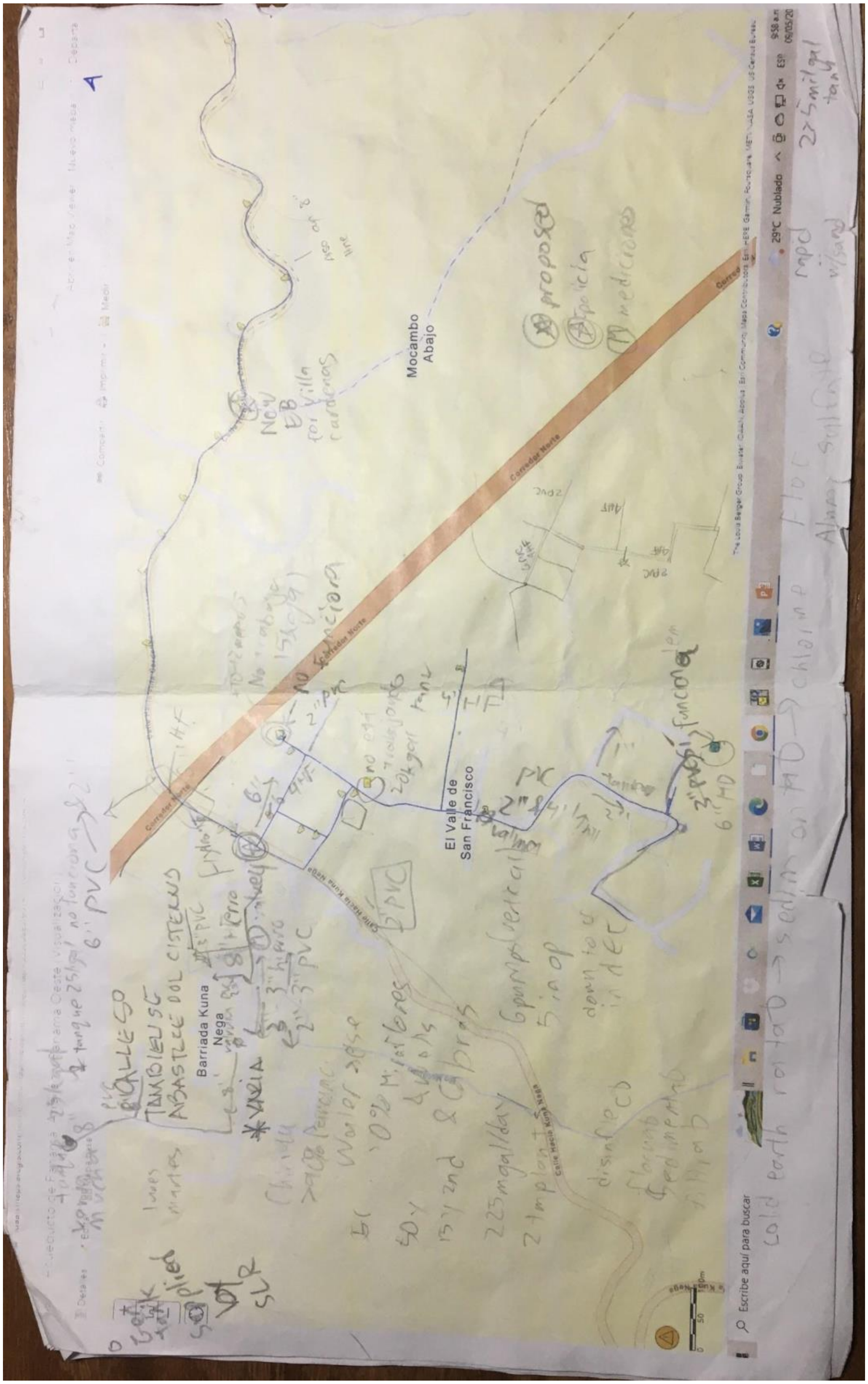
Notas:

Clientes: Toda persona que formaliza bajo un contrato con la institución, el uso de los servicios de agua potable y/o alcantarillado sani

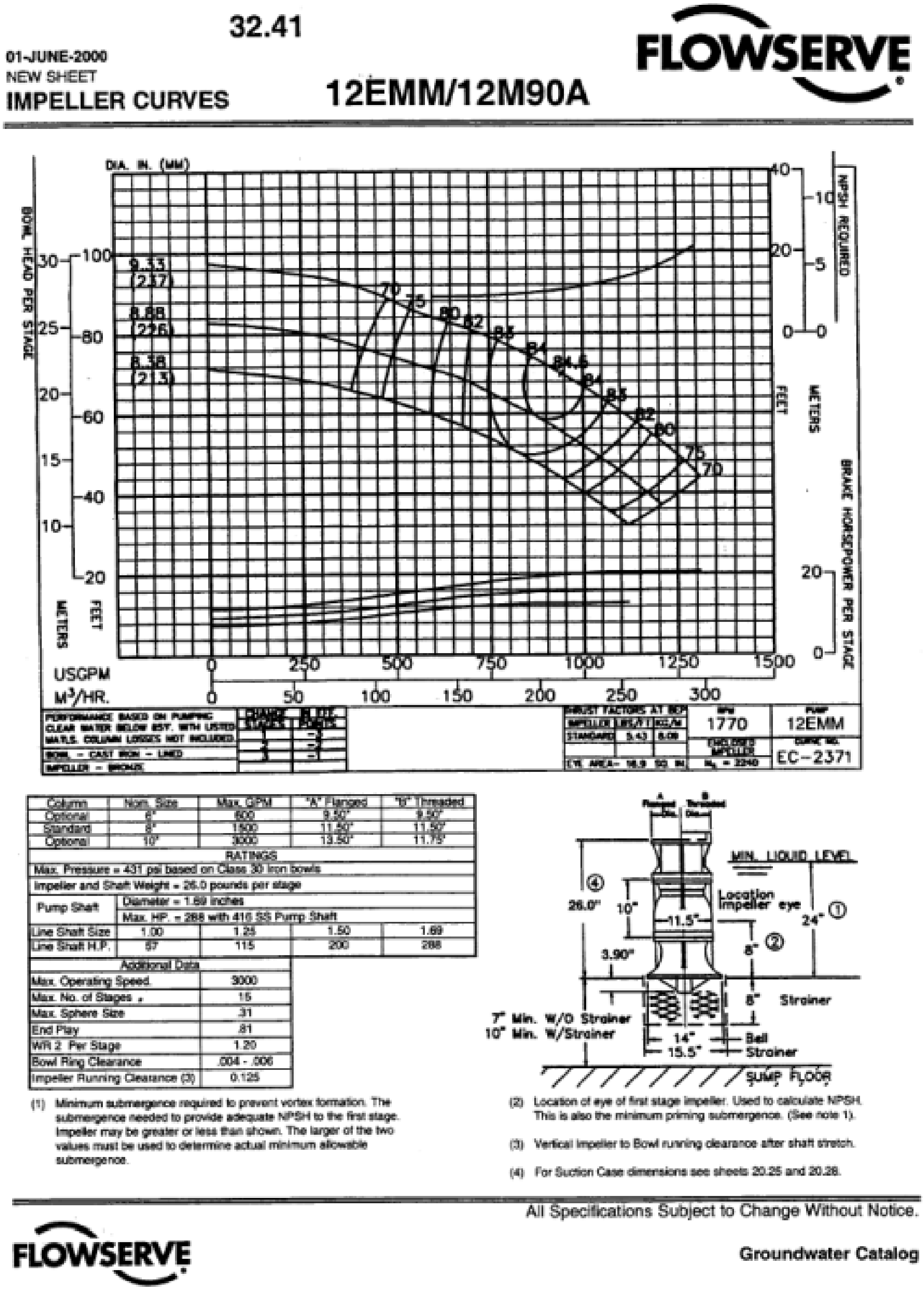
Usuarios ilegales: Usuario que cuenta con el suministro de agua sin un contrato con la institución, por lo que no están en la base de da

Potenciales: Son posibles clientes dentro de los lotes baldíos, fincas o terrenos que no cuentan con el suministro dentro del predio. De potenciales los que son abastecidos por pozos. En ninguno de los dos casos tiene contrato con la institución.

Corregimiento Kuna Nega Annotated Paper Map for ArcGIS



Chivo Chivo Pump Station Pump Curve Reference Sheet



Column	Nom. Size	Max. GPM	"A" Flanged	"B" Threaded
Optional	6"	600	9.50"	9.50"
Standard	8"	1500	11.50"	11.50"
Optional	10"	3000	13.50"	11.75"
RATINGS				
Max. Pressure = 431 psi based on Class 30 Iron bowls				
Impeller and Shaft Weight = 26.0 pounds per stage				
Pump Shaft	Diameter = 1.69 inches			
	Max. HP. = 288 with 416 SS Pump Shaft			
Line Shaft Size	1.00	1.25	1.50	1.69
Line Shaft H.P.	57	115	200	288

Additional Data	
Max. Operating Speed	3000
Max. No. of Stages	15
Max. Sphere Size	.31
End Play	.81
WR 2 Per Stage	1.20
Bowl Ring Clearance	.004 - .006
Impeller Running Clearance (3)	0.125

(1) Minimum submergence required to prevent vortex formation. The submergence needed to provide adequate NPSH to the first stage. Impeller may be greater or less than shown. The larger of the two values must be used to determine actual minimum allowable submergence.

(2) Location of eye of first stage impeller. Used to calculate NPSH. This is also the minimum priming submergence. (See note 1).

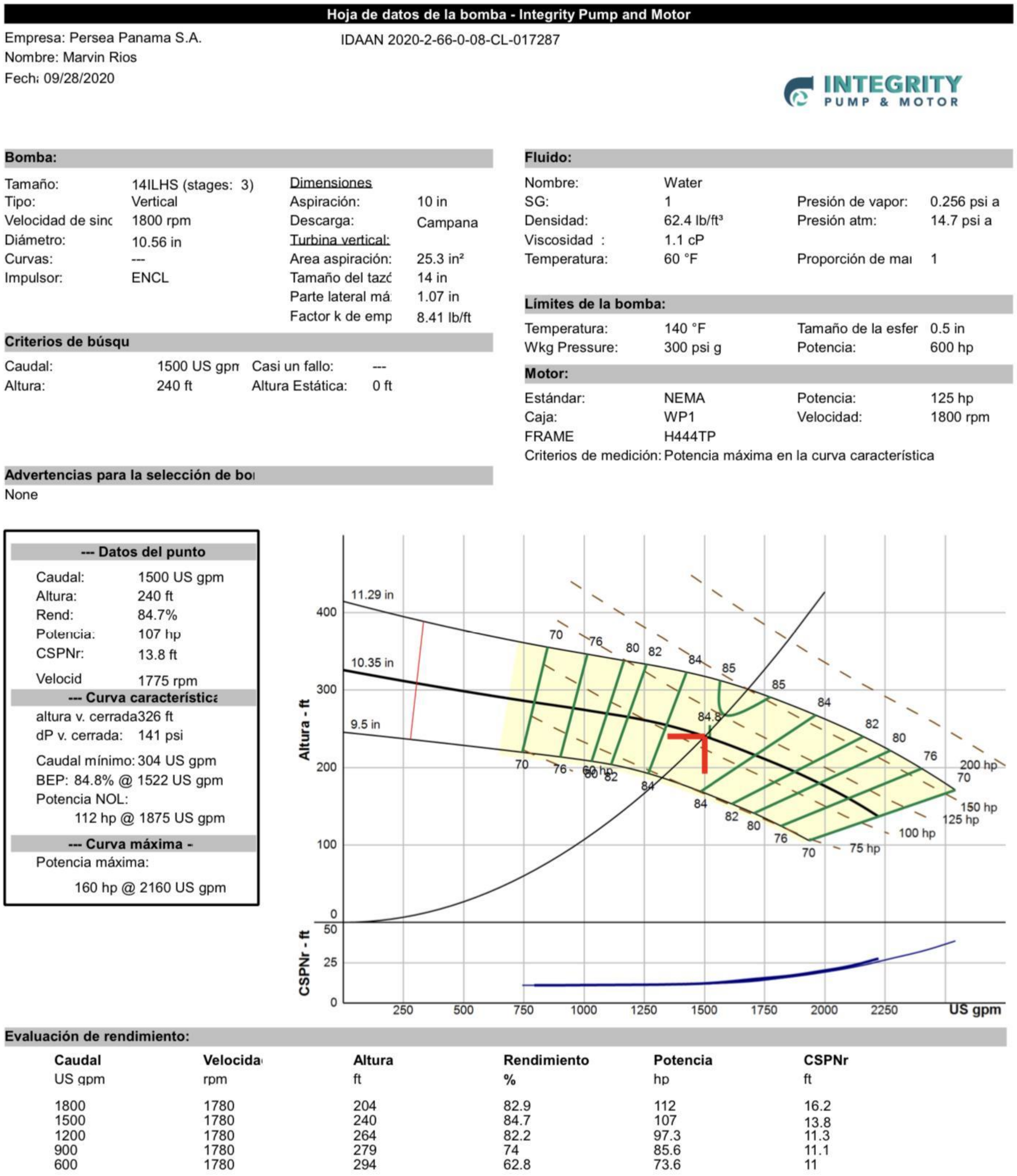
(3) Vertical impeller to Bowl running clearance after shaft stretch.

(4) For Suction Case dimensions see sheets 20.25 and 20.28.

FLOWSERVE

Groundwater Catalog

Patacón Pump Station Pump Curve Reference Sheet



Hoja de datos de la bomba - Integrity Pump and Motor

Empresa: Persea Panama S.A.
Nombre: Marvin Rios
Fech: 09/28/2020

IDAAN 2020-2-66-0-08-CL-017287

Bomba:

Tamaño:	14ILHS (stages: 3)	Dimensiones	
Tipo:	Vertical	Aspiración:	10 in
Velocidad de sinc	1800 rpm	Descarga:	Campana
Diámetro:	10.56 in	Turbina vertical:	
Curvas:	---	Area aspiración:	25.3 in²
Impulsor:	ENCL	Tamaño del tazó	14 in
		Parte lateral má	1.07 in
		Factor k de emp	8.41 lb/ft

Criterios de búsqu

Caudal:	1500 US gpm	Casi un fallo:	---
Altura:	240 ft	Altura Estática:	0 ft

Fluido:

Nombre:	Water		
SG:	1	Presión de vapor:	0.256 psi a
Densidad:	62.4 lb/ft³	Presión atm:	14.7 psi a
Viscosidad :	1.1 cP		
Temperatura:	60 °F	Proporción de mai	1

Límites de la bomba:

Temperatura:	140 °F	Tamaño de la esfer	0.5 in
Wkg Pressure:	300 psi g	Potencia:	600 hp

Motor:

Estándar:	NEMA	Potencia:	125 hp
Caja:	WP1	Velocidad:	1800 rpm
FRAME	H444TP		
Criterios de medición:	Potencia máxima en la curva característica		

Advertencias para la selección de boi

None

--- Datos del punto

Caudal:	1500 US gpm
Altura:	240 ft
Rend:	84.7%
Potencia:	107 hp
CSPNr:	13.8 ft
Velocid	1775 rpm

--- Curva característica

altura v. cerrada	326 ft
dP v. cerrada:	141 psi
Caudal mínimo:	304 US gpm
BEP:	84.8% @ 1522 US gpm
Potencia NOL:	112 hp @ 1875 US gpm

--- Curva máxima -

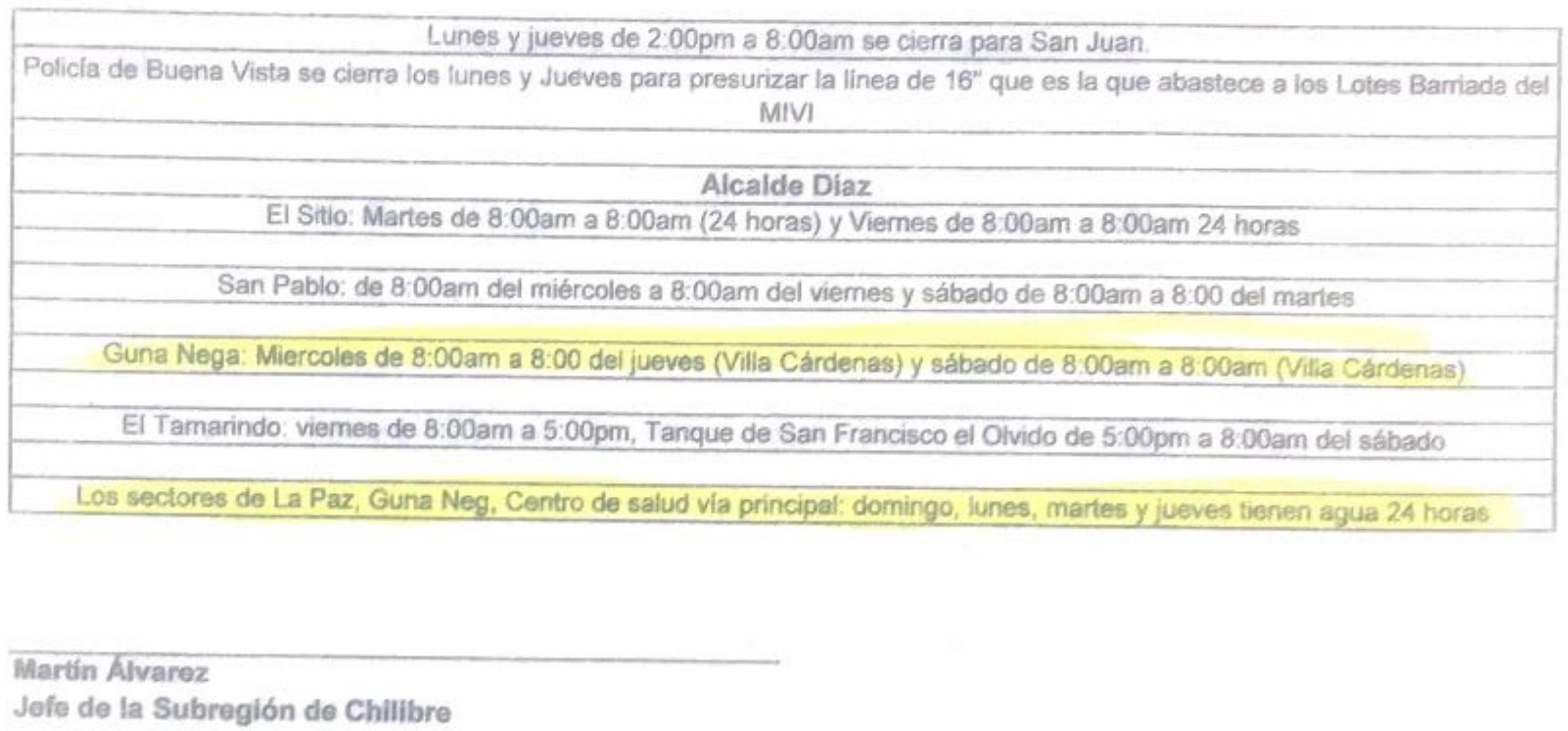
Potencia máxima:
160 hp @ 2160 US gpm

Evaluación de rendimiento:

Caudal US gpm	Velocida rpm	Altura ft	Rendimiento %	Potencia hp	CSPNr ft
1800	1780	204	82.9	112	16.2
1500	1780	240	84.7	107	13.8
1200	1780	264	82.2	97.3	11.3
900	1780	279	74	85.6	11.1
600	1780	294	62.8	73.6	11

Seleccionado del catálogo: Integrity.60, Versión 2.1.3

IDAAN's Water Delivery Schedule to Kuna Nega



Lunes y jueves de 2:00pm a 8:00am se cierra para San Juan.
Policía de Buena Vista se cierra los lunes y Jueves para presurizar la línea de 16" que es la que abastece a los Lotes Barriada del MIVI
Alcalde Diaz
El Sitio: Martes de 8:00am a 8:00am (24 horas) y Viernes de 8:00am a 8:00am 24 horas
San Pablo: de 8:00am del miércoles a 8:00am del viernes y sábado de 8:00am a 8:00 del martes
Guna Nega: Miercoles de 8:00am a 8:00 del jueves (Villa Cárdenas) y sábado de 8:00am a 8:00am (Villa Cárdenas)
El Tamarindo: viernes de 8:00am a 5:00pm, Tanque de San Francisco el Olvido de 5:00pm a 8:00am del sábado
Los sectores de La Paz, Guna Neg, Centro de salud vía principal: domingo, lunes, martes y jueves tienen agua 24 horas

Martín Álvarez
Jefe de la Subregión de Chilibre

Appendix C: Mathematics

Understanding the Hazen-Williams and Darcy-Weisbach Equations

Two equations have been developed to calculate pressure loss: the Hazen-Williams Equation and the Darcy-Weisbach Equation (*Hazen-Williams Equation - Calculating Head Loss in Water Pipes, 2004*).

$$\text{Hazen-Williams Equation: } H_{loss} = \frac{4.73L(\frac{Q}{C})^{1.852}}{D^{4.87}} \qquad (5)$$

$$\text{Darcy-Weisbach Equation: } P_{loss} = f\,\frac{l}{D}\frac{\rho V^2}{2} \qquad (6),$$

where,

$$f = f(Re, \frac{\epsilon}{D}) \quad (7)$$

$$Re = \frac{4Q}{\pi D \upsilon} \qquad (8)$$

The Hazen-Williams equation is empirical, meaning it is calculated directly using collected data (*Hazen-Williams Equation*, 2004). It calculates pressure loss (H_{loss}) based on length (L), flow rate (Q), Diameter (D), and Roughness Coefficient (C).

$$H_{loss} = \frac{4.73L(\frac{Q}{C})^{1.852}}{D^{4.87}} \qquad (10)$$

The pressure at the downstream node of a link is equal to the pressure at all upstream nodes minus pressure loss.

In comparison, the Darcy-Weisbach equation is more complex but more accurate. It is generally considered “to be the most accurate model for estimating frictional head loss for a steady pipe flow…since [it] requires iterative calculation” (*Hazen-Williams Equation*, 2004). It uses Length (l), Diameter (D), Density (ρ) and Velocity (V) and Friction factor (f) to calculate pressure loss (P_{loss}):

$$P_{loss} = f\frac{l}{D}\frac{\rho V^2}{2} \qquad (11)$$

$$\text{Velocity, } V = \frac{Q}{A} = \frac{4Q}{\pi D^2} \qquad (12)$$

$$\text{Since Area, } A = \frac{\pi D^2}{4} \qquad (13)$$

Combining the flow rate and original equation, you are left with:

$$P_{loss} = f\frac{8l\rho Q^2}{\pi^2 D^5} \qquad (14)$$

The friction factor is dependent on the Reynolds Number (Re) and $\frac{\varepsilon}{D}$, where D is the diameter and ε is the roughness, and both are measured in units of length. Each material has a unique roughness.

$$f = f(Re, \frac{\epsilon}{D}) \qquad (15)$$

The Reynolds number is a unitless number that describes whether flow is laminar, transitional, or turbulent. Laminar flow is orderly; water flows in straight lines. In turbulent flow, water swirls and eddies as it passes through the pipe. Transitional flow is a mixture of both. The Reynolds number is calculated using Density (ρ), Velocity (V), Diameter (D), and kinematic viscosity (ν) (*Analysis Algorithms*, n.d.).

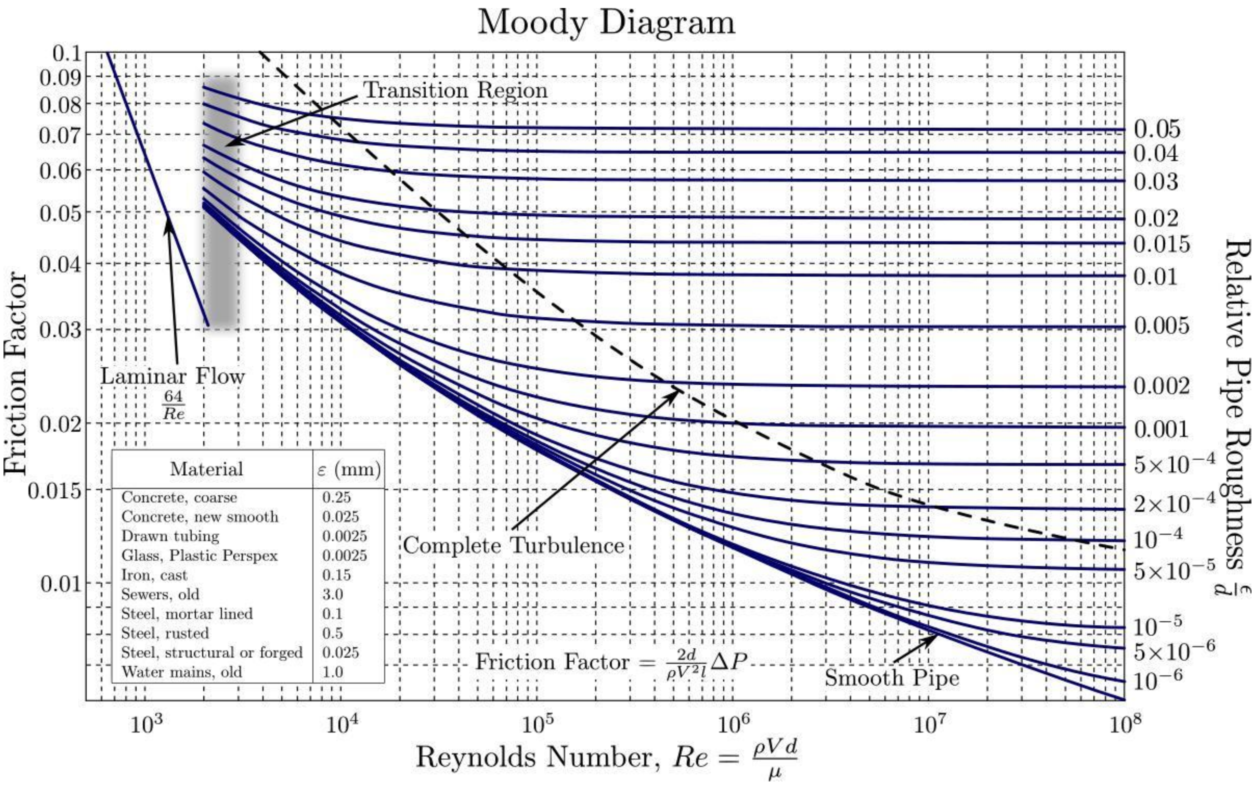
$$Re = \frac{4Q}{\pi D \upsilon} \qquad (16)$$

At Reynolds numbers below 2000, flow is laminar. At Reynolds numbers above 4000, flow is turbulent. Between 2000 and 4000, flow is transitional. To match the behavior of real water, EPANET uses different equations to calculate the friction factor for laminar, turbulent, and transitional flow (*Analysis Algorithms*, n.d.).

If (Re < 2000), then Laminar: $f = \frac{64}{Re}$ (17)

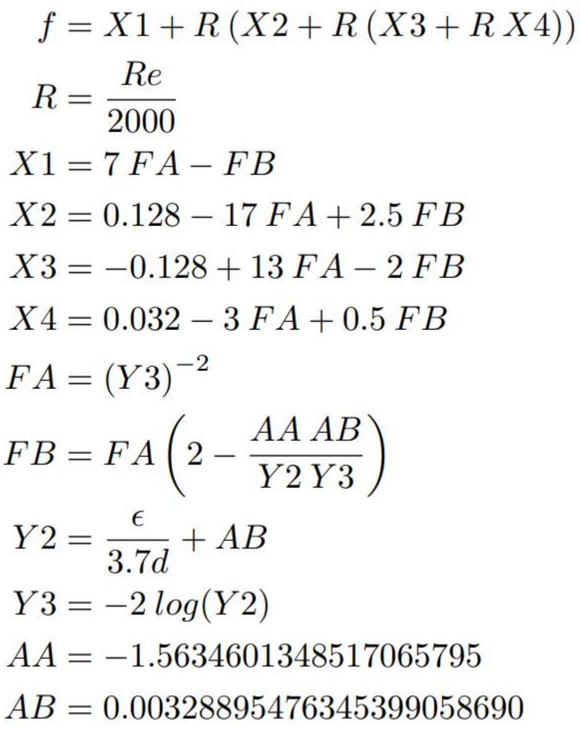
If (Re > 4000), then Turbulent: $f = \frac{0.25}{[log(\frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{0.9}})]^2}$ (18)

If (2000 < Re < 4000), then Transitional: the friction factor is calculated based on the Moody Diagram (Figure C.1). Figure C.2 shows these friction factor calculations.



Material	ε (mm)
Concrete, coarse	0.25
Concrete, new smooth	0.025
Drawn tubing	0.0025
Glass, Plastic Perspex	0.0025
Iron, cast	0.15
Sewers, old	3.0
Steel, mortar lined	0.1
Steel, rusted	0.5
Steel, structural or forged	0.025
Water mains, old	1.0

Figure C.1. The Moody Chart, above, is used to calculate friction factor in transitional flow (Moody Chart, 2019).



$$f = X1 + R\,(X2 + R\,(X3 + R\,X4))$$
$$R = \frac{Re}{2000}$$
$$X1 = 7\,FA - FB$$
$$X2 = 0.128 - 17\,FA + 2.5\,FB$$
$$X3 = -0.128 + 13\,FA - 2\,FB$$
$$X4 = 0.032 - 3\,FA + 0.5\,FB$$
$$FA = (Y3)^{-2}$$
$$FB = FA\left(2 - \frac{AA\,AB}{Y2\,Y3}\right)$$
$$Y2 = \frac{\epsilon}{3.7d} + AB$$
$$Y3 = -2\,log(Y2)$$
$$AA = -1.5634601348517065795$$
$$AB = 0.00328895476345399058690$$

Figure C.2. The calculations necessary to solve for the friction factor, f, in the case of transitional flow. It is "computed using a cubic interpolation formula derived from the Moody Diagram" (Analysis Algorithms, n.d.).

Glossary

Darcy-Weisbach Equation: One of two equations that describes pipe flow.

Demand: The quantity of water consumed by houses, measured in gallons per minute.

Hazen-Williams Equation: One of two equations that describes pipe flow.

HMO: Hydraulic Modeling Optimization. The process of using a computer model to improve distribution in a water network.

Junction: A point where a pipe ends, changes diameter, or intersects another pipe.

Leakage: Water lost, measured in gallons per minute. Leakage equals flow in minus flow out minus demand.

Link: A line in the model. It connects two nodes. A link represents a pipe or a pump.

Node: A point in the model. Links connect nodes. A node represents a junction or a tank.

Pump Curve: A graph that depicts the increase in pressure caused by a pump for each possible flow rate.

PVC: Polyvinyl Chloride. A type of plastic pipe, the most common in Corregimiento Kuna Nega.

Roughness Coefficient: A number that describes the friction caused by contact between water and the pipe.

Velocity of Flow: The speed of water, measured in feet per second.

Volumetric flow rate: The quantity of water passing through a point in the network measured in gallons per minute.