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TWO PUMPS, ONE VOLCANO: AN EPANET FEASIBILITY STUDY OF CONNECTING TWO GROUNDWATER PUMPS IN RURAL COASTAL COMMUNITIES IN WEST AMBAE, VANUATU

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TWO PUMPS, ONE VOLCANO: AN EPANET FEASIBILITY STUDY OF
CONNECTING TWO GROUNDWATER PUMPS IN RURAL COASTAL
COMMUNITIES IN WEST AMBAE, VANUATU

By

Helen A. Amiri

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Environmental Engineering

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2018

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This report has been approved in partial fulfillment of the requirements for the Degree of
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List of abbreviations

CWS	Continuous Water Supply
DoWR	Department of Water Resources
EPA	Environmental Protection Agency
GPM	Gallons per Minute
IWS	Intermittent Water Supply
LDS	Latter Day Saints
LJSS	Londua Junior Secondary School
LPCD	Liters per Capita per Day
LPD	Liters per Day
LPM	Liters per Minute
MOH	Ministry of Health
NDMO	National Disaster Management Office
NGO	Non-Governmental Organization
NHC	Ndui Ndui Health Center
OHCHR	Office of the United Nations High Commissioner for Human Rights
RWS	Rural Water Supply
UN	United Nations
UNICEF	United Nations Children's Fund
UNU-EHS	United Nations University Institute for Environmental and Human Security

Abstract

In situations where groundwater supply shows vulnerability, improving water distribution network resiliency can be desirable. To do so, one water source can be linked with another to provide a redundant source.

On the South Pacific island of Ambae, the water demands of its residents routinely exceeded supply. Residents had traditionally used rainwater collection as their sole water supply source. In 2017, groundwater drilling operations created an alternative water supply at two community institutions, Ndui Ndui Health Center and Londua Junior Secondary School. One borehole went dry during pump testing; the feasibility of linking these two boreholes is investigated herein.

EPANET is used to simulate the existing two intermittent groundwater supply units. EPANET is a hydraulic modeling program used to study pressurized water distribution systems. Several configurations connecting the two boreholes and supplying villages along the direct path joining the two sources are modeled. In doing so, the nature of the systems shifted from an intermittent water supply (IWS) to continuous water supply (CWS), improving water availability to the local population. The cost of materials and ongoing energy usage to operate the systems is analyzed. It is found that the capital costs of system upgrades were similar between the different models and such upgrades could be feasible. However, the high ongoing cost of operating generators to power the systems is beyond an economic level likely to be sustained by the local population.

Despite the benefits of connecting the two boreholes and shifting from IWS to CWS, the cost of ongoing operation of such a system is prohibitive to the local population. Due to issues surrounding the currently prevalent ashfall, this study did not examine the feasibility of using solar power as an alternative, nor did it explore low cost methods to improving water quality of collected rainwater mixed with ash. Such studies might prove fruitful at a later time.

1 Introduction

The United Nations has named ensuring access to drinking water and sanitation a main goal in their 17 Sustainable Development Goals. According to World Health Organization standards, each human being should have access to a minimum of 20 liters per capita per day (LPCD) to maintain basic health in emergency situations, according to the World Health Organization (WHO, 2011). Rainwater harvesting is a common supply method for many communities, but it may not always be sufficient during the dry season for people dependent on it.

Figure 1.1. Map of Vanuatu. Image Source: Google Earth, See Appendix A for full attribution and copyright licensing information.

Vanuatu, like many other nations in the South Pacific, uses rainwater harvesting to meet the water demands of its citizens, particularly in rural areas (Quigley et al., 2016). In certain parts of the country, the water demands are no longer being met by rainwater catchment and certain sectors are turning to groundwater drilling to meet those water needs.

Located on the Pacific Ocean's Ring of Fire, Vanuatu frequently experiences earthquakes, cyclones, volcanic eruptions, and is at risk for tsunamis. Vanuatu, the most disaster-prone country in the world, has many areas with critical water shortages (UNU-EHS, 2015). The challenges posed by natural hazards, combined with logistical issues across its 83 islands, are obstacles to the nation's ability to address water scarcity issues.

1.1 Ni-Vanuatu Water Management

The Vanuatu Ministry of Lands and Natural Resources is the government agency overseeing the functions of multiple departments, including those concerned with water. Previously, the Ministry of Lands and Natural Resources had two separate units to address water scarcity and supply. Urban areas (namely the two largest cities, Port Vila and Luganville) had central water supplies falling under the jurisdiction of the Water Resource Management office, while all other parts of the country were managed by the Rural Water Supply office. In early 2017, these offices were combined to form a new department, the Department of Water Resources (DoWR).

The Vanuatu Ministry of Health (MOH) retains responsibility for supplying water for its own health units. The MOH can seek outside funding and complete projects relating to supplying water to all public health institutions without the involvement of DoWR.

A multitude of NGOs and church humanitarian organizations work with rural communities to address water scarcity issues in an effort to supplement limited DoWR involvement. In the past, NGOs in Vanuatu have avoided using drilling due to negative experiences with the limited selection of drilling companies available for contract.

1.2 Water Practices on West Ambae

Ambae is an island located in Penama province, to the north of the country. The island is home to the moderately active Lombenben volcano, and its unique geology poses challenges to its residents with regard to water security. The only surface water perceived to be potable on the island is located in Lake Manaro Lakua, one of three crater lakes in the volcanic rim with traditional “kastom” significance. This space, sacred to island residents, is not a viable source for drinking water. With no surface water or groundwater access, residents have relied on rainwater to meet their drinking water needs.

Ambae residents use concrete cisterns (locally referred to as “wells”) to collect rainwater during the limited rainy season. Missionaries are anecdotally credited with the cistern design. There is typically one cistern located in each family compound. This water alone is meant to supply water for all domestic needs. Fish were historically placed in the cisterns to eat mosquito larva and prevent outbreaks of malaria and dengue.

Figure 1.2. Rainwater Catchment Cisterns in Ndui Ndui. Photo by author.

While such cisterns may have provided sufficient water in the past, this is no longer the case. Population growth and longer lifespans have increased pressure on limited water supplies. In addition, cisterns remain susceptible to contamination. As seen in Figure 1.2, even cisterns with lids are rarely screened to prevent debris, rats or lizards from entering the cisterns. Before the cisterns are empty, the contaminated water frequently causes water related illnesses in the local population. In July, the water level in cisterns starts to reach levels of concern. An uptick in water-related illnesses is witnessed annually at the local health center, and it is thought that the quality of the water turns poor by this time.

Another issue exacerbating water scarcity is the cultural shift and increase in consumption of kava. Kava (*Piper methysticum*) is a plant that traditionally was only consumed by chiefs at special ceremonies. Today, kava is becoming one of Vanuatu's biggest cash crops. What is not exported internationally and to other islands domestically is locally consumed daily by men and women. Kava, as it is prepared today, has a much higher water footprint than it did as it was once prepared. Interviews with local residents reveal that, in chiefly ceremonies, the kava root was cleaned with coconut fibers and then ground with a stone. The concentrated pulp was consumed in a half-coconut shell.

Figure 1.3. Cleaning of kava root in Tafea. Photograph by author.

Figure 1.4. Chewed kava pulp in Tafea. Photograph by author.

Figure 1.5. Kava pulp being strained to make into a beverage in Tafea. Photograph by author.

In other parts of Vanuatu, such as in the southern Tafea province, locals continue to clean kava with coconut fibers and chew the kava to create the pulp (examples of this are seen above in Figures 1.3 and 1.4). That pulp is then strained with water for consumption (see Figure 1.5), although the water footprint in the kava's preparation is significantly lower than that in other parts of the country. The average adult will consume two or three half-coconut shells of this more concentrated kava in an evening.

Today on West Ambae, kava root is cubed, then twice-rinsed to remove the dirt and bitter flavor. The root is then ground in a meat grinder; this pulp is subsequently strained as up to 20 liters of water per kilo of kava is poured over the pulp to make the beverage. Most adults will consume at least 600 ml in an evening, although drinking twice that amount is not unheard of. This shift in cultural practice accounts for a great change in water consumption patterns in a place so water scarce.

2 Purpose

In 2017, the MOH created an “agreement of understanding” with the humanitarian branch of the Church of Jesus Christ and Latter Day Saints church to jointly fund a groundwater drilling operation on West Ambae at Ndui Ndui Health Center. UNICEF was then approached to sponsor the drilling of an additional hole at Londua Junior Secondary School, to which they agreed. There was some discussion as to whether to connect the two boreholes; however, increased activity and ongoing eruptions of Lombenben volcano halted activity surrounding such a project.

The purpose of this report is to investigate the feasibility of connecting two boreholes to supply nearby communities with water and create redundancy in the system, making the overall system more resilient. This report centers on the boreholes on West Ambae to discuss benefits and costs relating to various configuration options.

Figure 2.1. Map of Existing Pumps and Proposed Tank Sites. Image Source: Google Earth, See Appendix A for full attribution and copyright licensing information.

EPANET was used to model several different configurations, each on 24-hour cycles. The first scenario simply models the system as it currently stands in West Ambae with two separate boreholes and no water being supplied to the three villages situated between them. The next scenarios examine three different ways to connect the boreholes to supply every village, but the two boreholes are not connected. The final scenario examines a connection that meets the water demands of each village and connects the two boreholes, creating redundancy in the network. Figure 2.1 illustrates this fully connected option.

3 Background

In September 2017, Vanuatu Drilling, a local drilling company, arrived on West Ambae as contracted by the MOH and the LDS church. Vanuatu Drilling was successful in drilling for water on the Ndui Ndui Health Center grounds. A pump test was conducted at several flow rates, and at one point the well went dry. It was determined that a safe pumping rate was approximately 100 LPM; this rate would allow adequate recharge of the freshwater lens, avoiding unsustainable pumping and reducing chances of saltwater intrusion from the nearby ocean. A pump with pipes, fittings, tanks and tap were all installed at the Ndui Ndui Health Center (NHC).

Figure 3.1. Installation of Submersible Pump at NHC. Photograph by author.

The following week, Vanuatu Drilling repeated the procedure at the nearby Londua Junior Secondary School (LJSS) under contract by UNICEF. Pump tests at LJSS indicated a greater reserve of water, as the well did not go dry. To be safe, the pump (identical to that installed at NHC) was also configured to operate at 100 LPM.

There were concerns regarding the water supply at the NHC, given the pump test results. Discussion arose as to the possibility of connecting the two boreholes in an attempt to create resiliency in the system given the vulnerability already observed. These discussions were halted on September 24, 2017 when Lombenben volcano was raised to a

level 4 alert level by the Vanuatu National Disaster Management Office, indicating ongoing minor eruptions. Citizens were encouraged to begin evacuating of their own accord. A few days later, NDMO announced mandatory evacuations of all residents of Ambae island.

In October 2017, the Vanuatu government lifted the evacuation order, permitting residents to return to Ambae. At this time, the author visited Ambae island accompanied by Jonathan Toomey (of Vanuatu Drilling) to check the condition of the two pumps and associated components. They were undamaged and fully operational.

3.1 Ndui Ndui District, West Ambae

Ndui Ndui District on the western side of Ambae island is home to over 500 residents. The most notable feature of the area is the NHC, which is the best equipped health facility in West Ambae. Prior to Vanuatu becoming an independent country in 1980, the NHC was under the administration of Church of Christ missionaries, who largely funded the upkeep of the facility. Today the facility is the primary health facility for all West Ambae residents (5,500+). For complex procedures or specialty care not available at the facility, patients must receive official referral from NHC staff for treatment elsewhere.

On the far northeastern end of Ndui Ndui district is Londua Junior Secondary School. The school retains ties to Church of Christ, although it is also government supported. Approximately 100 students reside at the boarding school from February until November each year.

Between NHC and LJSS along the coast are three villages: Nanako, Navitora, and Ambore. Each village contains a church. Ambore is also the location of the regional government administrative offices. Most people in the communities are small-scale subsistence farmers whose earnings go towards paying for school fees for their children and occasional improvements to their homes.

3.2 Seasonal Precipitation Patterns

The wet season in Vanuatu extends from November to May, although most rainfall on Ambae is typically observed from December to March. The location of a community affects the precipitation they might experience, particularly in the dry seasons.

Figure 3.2. Map of Penama Province. Image Source: Google Earth, See Appendix A for full attribution and copyright licensing information.

Like many other communities on the leeward (in Vanuatu’s case, western) side of mountains or volcanos, less rainfall is observed in Ndai Ndai than would be on the eastern side of Ambae. The center of Ndai Ndai district is marked in yellow in Figure 3.2. It is situated directly west of the volcano’s crater. El Niño patterns can exacerbate seasonal weather effects (Vanuatu Government Department of Meteorology and Geo-Hazards et al., 2011).

Climate change is widely accepted in Vanuatu and not as controversial as it is in the United States. Conversations with West Ambae residents reveal the water shortages have increased in duration and severity in the last decade compared with previous years; local residents attribute these shortages as evidence of climate change impacting their lives.

3.3 Water Use Behavior

Ambae residents collect rainwater in concrete cisterns on their family compounds. Some cisterns utilize the surface area of metal roofing and gutter systems to increase the collected volume, but many do not, as most local homes use natangura palm (*Metroxylon warburgii*) leaf roofing. Those without metal roofing collect just the rain that falls directly into the open cistern. Residential uses for water include cooking, drinking, washing clothes, household cleaning and nightly bathing. Most water is used before mealtimes and in the evenings for bathing. In the dry season, as water levels in cisterns drop, washing and bathing activities are often shifted to the ocean to conserve water. This conservation measure is easier for those residing on the coast and physically fit to navigate steep terrain to the ocean shore. During periods of extreme drought, salt water

from the ocean is used for cooking and only bottled water is available for hydration, with green coconuts being a more affordable (thus preferred) alternative.

At the health center and school, water uses are somewhat different. The health center, officially open from 8 AM-5 PM, uses most of its water during the day. Patients are attended to, and after that time the buildings are cleaned by staff. Washing patient bedlinens and cleaning medical instruments occurs during the daylight hours, when most water will be used. Although the health center is responsible for a large population, the daily patient load is relatively small, and the majority are outpatient clients whose water footprint is more accurately reflected in domestic household tallies. The demand is meant to reflect that of the health center and a small number of patients admitted for observation and their accompanying familial caregivers.

Londua Junior Secondary School serves as a boarding school, continuously housing approximately 100 students and faculty on site from February until November. Students are required to bathe in the ocean year-round due to limited water availability. Water on campus is mostly used for drinking, cooking, cleaning and limited washing of clothing. Many students bring dirty laundry home on weekend visits, if they are able. In the past, when the school has completely run out of water, students were sent home until the following term.

Although the consumption of kava was a noted concern above, in the area of study only two nakamals (kava bars) were intermittently operational during the author's 18-month residence in West Ambae. These nakamals are located far away enough from the proposed water tap sites that their use of water is unlikely to draw from the proposed water supply. As such, their water footprint is not included in this study. The Ndui Ndui coastal areas are openly disapproving of kava consumption; residents of the coastal villages often hike uphill to find nakamals open for business.

3.4 Resiliency

As stated above, one of the boreholes went dry during pump testing. While reducers were put in to prevent reoccurrences of the incident brought on by over pumping during the pump test, the event highlighted vulnerabilities in the system design as it was installed. If either the borehole at NHC or LJSS were to go dry due to unforeseen hydrogeological changes, that site would lose all groundwater access and the pumping system at site would go offline. By linking the two water sources through a pipe network, the redundant source would improve the resiliency of both systems. Both the school's and health center's populations depending on access to the groundwater would continue to be served in the event of one source going offline.

3.5 Water Quality

As stated in sections above, contamination issues can be present in the stagnant, open cisterns used by local residents. Intermittent water supply (IWS) is also associated with health risks that arise when pressures in pipes are low enough to draw water from the ground into any leaky pipes. Even when water quality of a source is similar between an intermittent water supply system and a continuous water supply system, water systems running intermittently have been shown to have higher levels of indicator bacteria than systems operating continuously (Kumpel and Nelson, 2013). When modeling possible upgrades to the water network, shifting from an IWS mode of operation to that of a continuous water supply would likely improve water quality, providing an added benefit to the system.

4 Methods

EPANET is used to study pressurized water distribution systems (Rossman, 2000). This study used EPANET to create a hydraulic model of the existing two boreholes, pumps, tanks, pipe material (roughness), and taps in West Ambae and investigated possible ways to expand and connect them.

Google Earth was used to gather elevation data for the pumps and tanks as they are currently situated and prospective tank locations. The author used knowledge of the local communities to select possible locations for tanks and taps that would be unlikely to incite land disputes, if built. The designs below follow the public road, for which no formal egress would be required.

Demand was estimated at 20 LPCD. The population reported by village leaders during the author's time residing on the island was used as the current population figures, rounded up to the nearest ten people. The World Bank's population growth figure for Vanuatu (2.2%) was used to project populations in the area over the design life of the project (30 years) (World Bank, 2018). The demand estimated at each node was for the projected population at the end of the project's design life. Figures illustrating how these demand patterns were input into EPANET to model a 24-hour cycle can be found in Appendix B.

For the cost estimate analysis, current local retail prices in Port Vila (Vanuatu's capital city) were used with the exception of mazut (a heavy, low quality fuel), for which West Ambae prices were used. At the time of writing, mazut and oil were both readily available on West Ambae with limited interruptions in shipping. The cost of energy usage for the generator to power the two pumps was included in this estimate; however the cost of oil and gas products can be extremely volatile. The cost of shipping goods between islands can be highly variable and, as such, were excluded from this analysis. Labor costs were excluded for similar reasons. A lengthy discussion of these reasons can be found in Appendix C. The design for tanks proposed in the villages follows the wire-reinforced ferrocement tank design promoted by Catholic Relief Services (Gendrano et al., 2006). The materials used in the tank construction and pipe network can be found in Appendix C.

Analysis was run for a 24-hour cycle of operation with each of the simulations. Tanks were assumed to be full at the start of the simulation. In the first scenario with no change to the system, the system was simply modeled as is. In modeling additional scenarios, controls were added to the pumps to connect them with their nearest tanks (as these showed the greatest volatility during simulations). The reason these controls were added was due to the increased size in the system. Running pumps all day would be expensive, unfeasible, and unnecessary as the modeling shows below. Figures showing the schematic of these EPANET renderings can be found in Appendix D. EPANET input data can be found in Appendix E.

5 Results

Google Earth was used to create an elevation profile for the proposed piping route of the water network. This was combined with measured groundwater levels taken during the installation of both pumps.

Figure 5.1. Elevation Profile

Although Figure 5.1 illustrates that water level at the borehole at Londua Junior Secondary School is lower than at Ndui Ndui Health Center, the difference in tank elevation at the NHC from its tap is greater than other tank locations in the network. This difference in head was required to raise pressure to 15 PSI. This additional head requires a great deal more work from the pump located at NHC than would otherwise be expected given the elevation profile (for tank elevations and other EPANET inputs, see Appendix E).

EPANET was used to simulate the system as it currently exists. Entering the demand pattern for just the health center and school, results show that the pressure at the outlets remains below 15 psi continuously, despite a high-volume storage capacity and pumps running continuously over a 24-hour period. These outlets at NHC are labelled “Node 3” in the model schematic; similarly, the outlet at LJSS is labelled “Node 7” (see Appendix D for detailed system maps).

Figure 5.2. Pressure vs Time (in current system)

As shown in Figure 5.1, the outlet pressure at NHC (Node 3) goes negative in the afternoon. The outlet at LJSS (Node 7) never goes negative, but approaches zero as the day goes on. EPANET is programmed to satisfy the input demand, even if that water is not yet in the tank to do so; this results in the negative pressures seen in Figure 5.2. It is unlikely the system could operate continuously for a second cycle without also reaching negative pressures. These results are in no way surprising; the system was never designed for continuous operation. The system was designed to allow operators to turn on generators intermittently to run the pumps as required; on average, the pumps would run 6 hours each day, twice a week.

In redesigning and expanding the system along the coastal route, upgrades in pressure and standard of operation are implied. The tanks are elevated to increase head to meet the minimum design pressure of 15 psi. Three villages lie in between the pumps at NHC and LJSS; all four possible network configurations were examined without connecting the two pumps via pipe network. Pumps would need to operate daily and pressure would remain above 15 psi at all times except during late night hours at NHC and LJSS when usage is unlikely. This could negatively impact water quality in the system. These pressures are still an order of magnitude higher than current pressures and with pressures dipping just below 15 psi at LJSS and those at NHC just below 14 psi at their lowest. In the final configuration, the two pumps and the three villages in between were all connected, creating a more resilient system through redundancy in the supply network.

Table 5.1. Energy Usage and Costs

	Option	Pump	Percent Utilization	Hours	Kw-hr/Mgal	Capital Cost (US)	Generator Cost (US)
Current System (As Is)	A	NHC	7.1429	1.71	208.6	\$ -	\$ 126,904.95
		LJSS	7.1429	1.71	352.67		\$ 126,904.95
Break Between NHC and Nanko	B	NHC	45.83	11.00	439.51	\$ 12,866.73	\$ 816,347.60
		LJSS	16.67	4.00	466.1		\$ 296,853.67
Break Between Nanko and Navitora	C	NHC	45.83	11.00	442.36	\$ 12,683.02	\$ 816,347.60
		LJSS	20.83	5.00	464.94		\$ 371,067.09
Break Between Navitora and Ambore	D	NHC	45.83	11.00	442.21	\$ 13,133.64	\$ 816,347.60
		LJSS	20.83	5.00	464.67		\$ 371,067.09
Break Between Ambore and LJSS	E	NHC	45.83	11.00	442.27	\$ 13,032.69	\$ 816,347.60
		LJSS	20.83	5.00	464.61		\$ 371,067.09
Fully Connected	F	NHC	45.83	11.00	442.11	\$ 13,402.84	\$ 816,347.60
		LJSS	16.67	4.00	465.97		\$ 296,853.67

As seen in Table 5.1 above, these options have a range of costs associated with their implementation. The percent utilization of each pump reflects how often the pump is on during the 24-hour simulation cycle. This was not the case for the “Current System” (Option A), as it would not reflect current operating practices; observed practices were substituted for the purposes of estimating the cost of operating the generator. The percent utilization was converted to hours, from which the cost estimate for operating the generator over a 30-year period was derived (see Appendix C). The capital costs included parts, no labor or shipping, and used present day prices. Capital costs were similar between the various options because the main difference between Options B-F was a select length of pipe but all other parts remained the same. The distance between the villages (and taps) is not far, so the difference in capital costs wouldn’t be very different (see Appendix D for pipe attributes and Appendix C for costs per unit pipe length).

These different options serve a different number of users with each pump.

Figure 5.3. Number of People Served in Each Community by Pump (Option A)

As shown in Figure 5.3, only those in the immediate area of each pump is served under the current water system. The blue and orange bar indicates water coming from NduiNdui on the left of the system (Fig. D.1) and from Londua on the right, respectively. If either borehole goes dry, the other population continues to have access to water, but there is no easy access for the other community. The three villages between the two pumps are not served by the current water network; users would need to walk or take other transport to the pumping locations.

Figure 5.4. Number of People Served in Each Community by Pump (Option B)

Option B greatly increases the number of users served by the network with the expanded area coverage. This system is more efficient than Options C-E, as outlined in Table 5.1 regarding generator usage. All three villages are linked with the pump at LJSS; if there is a pipe damaged between LJSS and Ambore, all villages lose access to water. If such

damage occurs between Navitora and Ambore, users in Nanako and Navitora lose coverage. Finally, a damaged pipe between Nanako and Navitora would affect only users in Nanako village.

Figure 5.5. Number of People Served in Each Community by Pump (Option C)

Option C serves the same number of users as Option B. This system is less efficient, using one more hour of generator time than Option B (see Table 5.1). Only two villages are linked with the pump at LJSS, while Nanako is linked with the pump at NHC. If there is a pipe damaged between LJSS and Ambore, users in only two villages lose access to water. If such damage occurs between Navitora and Ambore, users in just Navitora lose coverage. Finally, a pipe is damaged between Nanako and NHC, it would affect only users in Nanako village.

Figure 5.6. Number of People Served in Each Community by Pump (Option D)

Option D serves the same number of users as Option B and Option C. This system is as efficient as Option C, but less efficient than Option B (see Table 5.1). Only Ambore village is linked with the pump at LJSS, while two villages are linked with the pump at NHC. If there is a pipe damaged between LJSS and Ambore, users in Ambore lose access to water. If such damage occurs between Navitora and Nanako, users in only Navitora lose coverage. Finally, a pipe is damaged between Nanako and NHC, it would affect users in Nanako and Navitora villages.

Figure 5.7. Number of People Served in Each Community by Pump (Option E)

Option E serves the same number of users as Option B, Option C, and Option D. This system is as efficient as Option C and D, but less efficient than Option B (see Table 5.1).

In this configuration, all three villages are linked with the pump at NHC. If there is a pipe damaged between Navitora and Ambore, only users in Ambore lose access to water. If such damage occurs between Navitora and Nanako, users in Navitora and Ambore lose coverage. Finally, a pipe is damaged between Nanako and NHC, it would render users in all three villages without water.

Figure 5.8. Number of People Served in Each Community by Pump (Option F)

Option F serves the same number of users as Option B-E. This system is Option B (see Table 5.1); in all likelihood, the water flows the same way in Option F as it would in Option B. The main difference in this configuration is that both pumps are able to pump water into all three villages and the community housing the other borehole. There is redundancy in the network; if one borehole goes dry, the other can supply the entire network with water. For example, if there is a pipe damaged between Navitora and Ambore, users in all locations continue to have access to water; users in Nanako and Navitora remain connected to the pump at NHC, while users in Ambore remain connected to the pump at LJSS. No matter the location, if a single pipe is damaged or borehole goes dry, all users retain access to water. Such a configuration keeps users supplied with water while repairs are underway, should the need arise.

Figure 5.9. Capital and Energy Cost vs % Population Served

Figure 5.9 plots the combined capital and energy costs of each option over the thirty-year project lifespan against the percent of the total local population served. From the figure, it is clear that most of these options are similar in their service capacities to the local population. Option A costs substantially less while Options B-F are similar in cost over the thirty-year term (options ascend by cost along the Y-axis).

Figure 5.10. Capital and Energy Cost vs % Redundancy

Figure 5.10 better differentiates between the various options by plotting the capital cost of each option against the percent redundancy of the total population. In this circumstance, percent redundancy refers to the percentage of the population served that would continue to have access to water if a single pipe were to break in the system. The plot above examines the worst-case scenario for each option, meaning it plots the percentage of the total local population that would still have access to water if the pipe were to break in the place where it would leave the greatest number of people without water.

5.1 Redundancy Example

Redundancy is defined in this report as the percentage of the population who would retain access to water services if a single break in the system were to occur at the worst point. To illustrate this process, redundancy in Option B will be further detailed.

Figure 5.11. Break in Option B

In this example, a break has occurred at the X between Ambore village and Londua Junior Secondary School (see Figure 5.11). In Option B, this would disrupt water being supplied to all three villages, but water would continue to be supplied on location at Ndui Ndui Health Center and at Londua Junior Secondary School.

To calculate the percent redundancy, one would subtract the combined population left without water from the total population, then divide the resulting number by the total population. Using the current population, in Option B this would result in 200 people not having water across the three villages. The remaining population of 120 between the NHC and LJSS would still have access to water, leaving a redundancy of 38% of the total population. (For present population values by village, see Table B.1 in Appendix B).

This procedure was followed to calculate percent redundancy in Options B-F. In Option A, the borehole serving a greater number of users (LJSS) was taken offline to calculate percent redundancy for the overall community.

6 Discussion

When looking at different options for providing water to a population, there are several costs to consider. One can consider capital costs, operating costs, and ease of access for the population.

In the different scenarios outlined above, the capital costs are not a likely driving force in the decision-making process. There are no capital costs to consider if the system is left as it is, with coverage provided to just NHC and LJSS. If the decision is made to upgrade the system and provide coverage to the nearby communities, the relatively modest difference in capital costs doesn't assist in choosing between the different options. The capital cost difference between the most expensive option (to connect both boreholes with all of the communities) and the least expensive capital cost option (not connecting between Nanako and Navitora villages) is less than \$800.

This relatively small difference in capital costs is negligible when compared with the lower operating costs of other options. One could compare Option C with Option B, which is relatively similar at first glance. Geographically, Nanako village is closer to NHC than Navitora village. However, to reach Nanako from NHC, one must climb a hill. From a design standpoint, connecting Nanako with Navitora is a more efficient choice. Although this option is \$180 more expensive in capital costs, it actually saves an hour of running the LJSS generator each day. Over the course of only its first year of operation, the savings in mazut and oil alone is over \$1800, more than covering the additional capital cost.

Expanding the network would upgrade the pressure of the water delivery, but more importantly to local residents, improve access to water resources within the communities. This design assumes that residents would draw 20 LCPD. This assumption is unlikely to be true during the wet season, when rainwater cisterns are likely to be full. The roads on Ambae become muddy to the point where people lose their sandals to the muck while walking; it is unlikely that anyone would venture beyond their yard for water during such a time to carry heavy loads on unimproved road surfaces. The rainy season coincides with the school break; primary and secondary schools, including LJSS, are often boarded up and left without a caretaker during the school break. During this time, access to the generator to turn on the pump to supply communities with water would be limited, if available at all. Residents would likely start using the water supply in earnest beginning in June, lasting until November when seasonal rains typically begin. Estimating usage, as such, dramatically decreases expected operating costs (seven months of scheduled usage instead of twelve), and would more accurately reflect the true demand of users on the ground.

Table 6.1. Seven-Month Generator Operation Cost For 30-Year Project Lifespan

	Option	Pump	Full Year Generator Cost (US)	7 Month Generator Cost (US)
Current System (As Is)	A	NHC	\$ 126,904.95	\$ 74,027.88
		LJSS	\$ 126,904.95	\$ 74,027.88
Break Between NHC and Nanko	B	NHC	\$ 816,347.60	\$ 476,202.77
		LJSS	\$ 296,853.67	\$ 173,164.64
Break Between Nanko and Navitora	C	NHC	\$ 816,347.60	\$ 476,202.77
		LJSS	\$ 371,067.09	\$ 216,455.80
Break Between Navitora and Ambore	D	NHC	\$ 816,347.60	\$ 476,202.77
		LJSS	\$ 371,067.09	\$ 216,455.80
Break Between Ambore and LJSS	E	NHC	\$ 816,347.60	\$ 476,202.77
		LJSS	\$ 371,067.09	\$ 216,455.80
Everything Connected	F	NHC	\$ 816,347.60	\$ 476,202.77
		LJSS	\$ 296,853.67	\$ 173,164.64

In the final column in Table 6.1, the 30-year generator operating costs are more accurately reflected, painting a more realistic picture concerning the cost of operation only during months experiencing water scarcity. Decreased operating time dramatically reduces costs, but also calls into question the ability for the system to pay for itself.

For a project such as this, procuring funding for capital costs is less problematic, but funding recurring costs (such as mazut, oil and maintenance) is not easy. Many small-scale rural water supply networks depend on a monthly household fee to fund repairs or maintenance; such a structure would be culturally appropriate in this setting.

It stands to reason that if no system upgrades were made, NHC and LJSS would pay the costs associated with their respective systems. If community members came to these locations with containers to purchase water, these institutions could charge what they deem fair.

It is important to examine a local fee structure based on a monthly collection. To do so, one can examine a single year of fees in the “As Is” choice (Option A), “Break Between NHC and Nanako” (Option B), and “Fully Connected” (Option F). Option B was chosen for this comparison because it has the most efficient design and, thus, lowest operating

times of the various “Break” options; these fees would be lower than those of the other two choices.

Table 6.2. Comparison of Fees Per Month Per Household Under Different Networks

	Current System			Break Between NHC and Nanako			Fully Connected		
Location	Households	Annual Cost	Monthly Fee	Households	Annual Cost	Monthly Fee	Households	Annual Cost	Monthly Fee
NHC	1	\$ 3,068.34	\$ 255.70	1	\$ 19,737.88	\$ 1,644.82	1		\$ 54.71
Nanako	14			14	\$ 7,177.41	\$ 209.34	14	\$26,915.29	\$ 765.88
Navitora	22			22		\$ 328.96	22		\$ 1,203.53
Ambore	3			3		\$ 44.86	3		\$ 164.12
LJSS	1	\$ 3,068.34	\$ 255.70	1		\$ 14.95	1		\$ 54.71

If system upgrades were to occur, the increased operating fees would need to be shared by the public. The costs in Table 6.2 examine generator costs on an annual and monthly basis and compare them between different network configurations. The current system has few hours of operating time each week, but are fully paid for by the two institutions that house the pumps. To expand the network into nearby villages and extend the operating hours in the most efficient way (“Break Between NHC and Nanako”) without fully connecting the two boreholes, this method would share the cost of extended operation with the communities, partially subsidizing the school's costs. The final option under “Fully Connected” that connects the two boreholes and creates resiliency for the water supply of the two institutions would reduce costs for each institution from their current rates today. This final option shifts the majority of the operating cost to the communities that would have the highest demand.

In the event of a break in the fully connected schematic (Option F), the monthly generator fees would be slightly higher until the break was fixed (with the water delivery behaving similarly to that in Option E). If in the first year of operation the normal monthly cost of fuel and oil was a total of \$2,242.94 US, the cost during a month-long break in the system would raise that cost to \$2,392.47 US, a difference of \$149.53 US. This would burden each household by almost an extra \$4 per month, a locally significant amount. However, if someone were to deliberately cause a break and their identity was known, imposing a fine of \$150 US would be culturally appropriate and similar offences have such fines in the community.

Other variations of these outlined above could exist. The fee structure outlined above in “Fully Connected” has villagers largely subsidizing the water costs at West Ambae’s largest health facility, a cost that could be distributed amongst a wider population than the immediate villages through a different fee structure. Alternatively, NHC could remain with low pressure while LJSS could improve their system and expand to communities, for example, keeping NHC pump operating costs lower. However, even such an option would fail to provide resiliency in the network. If users were paying fees for such a system, they would expect access. Any vandalism to a system without both boreholes connected would be result in service disruptions for any users downstream from the disruption point; unacceptable given the cost of service.

This requires the consideration of the users' ability to pay. The wealthiest community members in rural Vanuatu are salaried government employees (e.g. teachers and nurses). Although it varies by province, the average rural teacher will earn \$500 US per month. The analysis outlined in Table 6.2 puts a monthly house fee at approximately \$55 US, above what most locals could afford (and those who could would likely be unwilling to spend so much on water alone). A more reasonable fee would be \$5 per household per month and even then, 1/3 of the users would be expected to be delinquent with fees. Fees one could reasonably expect to collect could not begin to cover the cost of the mazut and oil required to run the generator; any maintenance or repair fees would be an additional cost not addressed in this analysis.

Another point to consider is the timing of this analysis. This analysis was performed with the population numbers prior to the eruption of Lombenben volcano in late September 2017. While some residents have returned to the island, many have chosen to relocate to islands away from the volcano. A lower number of residents would decrease the overall water demand, but would increase fees each household would pay. The lower number of residents would suggest that perhaps water being captured in cisterns might again be sufficient for washing and cleaning activities, but some groundwater might be required depending on the water quality from the cistern and its potability.

Table 6.3. Distances from Communities to Nearest Groundwater Access Points

Location	Distance to Nearest Pump (ft)	Distance to Nearest Pump (km)
NHC	0	0.00
Nanako	1430	0.44
Navitora	2280	0.69
Ambore	1320	0.40
LJSS	0	0.00

The communities in between these two groundwater pumps are situated along the coast. As seen in Table 6.3 above, these communities are within a kilometer to the nearest groundwater pump, which would take a maximum of 20 minutes to reach each way. This is undesirable, but far below the average journey of 6 km endured by those in Africa and Asia to water sources (OHCHR, 2010).

7 Recommendations

The report above introduced three options for water networks in the Ndui Ndui district of West Ambae. The first scenario was to keep the system as it stands today; there are two boreholes within a couple kilometers of each other operating separate pumps and filling tanks on their respective premises. This option has no additional cost to the community, as it is already there. Individuals in need of water can approach these institutions in times of dire need to collect water, although these systems are designed to run intermittently and might not have a steady supply. When water is supplied at these institutions, it is done so at a very low pressure.

The second scenario examined different ways to connect the three villages in between the two supply points, without connecting the two boreholes. There were three different ways to do so, the most energy efficient design of these three was to connect the three villages to the LJSS water supply pump and avoid pumping water uphill from NHC. Although this design was not the least expensive option with capital costs, the design was so much more efficient that the savings in running the generator in the first year alone more than covered the capital cost difference between these options. This option had a monthly user fee 11 times what the local population would be likely to pay, and this fee would not cover maintenance or repair costs. There was also no system resiliency; if one pipe were to be vandalized, users from that break point and those further downstream would be without water.

The final option examined connecting all three villages to both boreholes. This option was within \$1000 of the second option in terms of capital costs. Although the overall cost of operating generators would be the same as that in Option B above, the monthly user fee would likely be much higher as it would at least partially subsidize the operation of the pump at NHC. This option would provide resiliency to the water supply line; the system could experience a single break at any point, and all users would continue to have access to water.

With the small number of households in the villages, the operating costs of the generators alone would be locally unsustainable. Even if capital costs were paid for with external funding, labor, maintenance and repairs were donated and no major weather disturbances were to affect the operation of the system (an unlikely scenario in Vanuatu), just the fees associated with running the pumps to supply 20 LCPD would be at least 11 times beyond what most families could afford. If the volcano remains active on Ambae, the recommended option between the three examined in this report is the first one: leave the water supply network as it is. These intermittently run pumps provide water to two major institutions according to demand; they are managed on the premises, with a low risk of vandalism. With these two sources available, those who need access to water can go to the source and pay a small on-demand user fee. If the volcano were to someday become less active and the number of households were to increase, the additional number of users in the network might make the shared monthly costs more affordable. In such a scenario,

connecting the two boreholes (Option F) to make a resilient system would be recommended.

8 Conclusion and Future Study

Although it can be desirable to upgrade water systems to meet minimum water demand standards to help communities easily meet their health needs, the sustainability of such systems must be considered in the design process. EPANET was used in this study to model an existing groundwater supply and develop alternative models to the existing system. Although different options were considered that pumped water to collection points closer to user communities and created some resiliency in the network in one option, the energy requirements to run the pump were higher than local residents could likely afford to pay at this time. A great deal of uncertainty surrounds the prospects on the island due to the volcano's continuing activity; this uncertainty affects local population numbers, public health issues, employment opportunities, the frequency of shipping routes, and whether people will even continue to live in the area.

This case study examined such costs in relation to coastal communities in between two water sources. This work did not investigate the possibility of solar power operation of the pumps, as the technical expertise in communities to maintain solar powered pumps is limited. As local technicians gain proficiency in maintaining such technologies, an investigation of the feasibility of using solar powered pumps might be more appropriate once ashfall is no longer as prevalent on the western side of Ambae. Biofuels are not currently being produced in Vanuatu; investigating the feasibility of using biofuels to power generators to power water pumps may become relevant in the future. Given uncertainty surrounding the effect of volcanic ash on water quality stored in existing community cisterns, additional work could be done surveying the water quality and, if found to have adverse effects to human health, finding locally viable treatment options.

9 Reference List

- Department of Public Works, City of Lincoln, NE (2018). “Calculating Inflation Factors for Cost Estimates”. Retrieved at <https://lincoln.ne.gov/city/pworks/engine/dconst/gpp/pdf/inflation.pdf>
- Gendrano, Jose Carmelo, Christopher Hillbruner with Michelle Neukirchen (2006). “The Banga Pinoy: A Design and Construction Manual for Wire-Reinforced Ferrocement Jars” *USAID and Catholic Relief Services*. Retrieved from <https://www.crs.org/sites/default/files/tools-research/banga-pinoy-design-and-construction-manual-for-wire-reinforced-ferrocement-jars.pdf>
- Knoema (2011-2018). “Vanuatu - Average consumer prices inflation rate”. Retrieved from <https://knoema.com/atlas/Vanuatu/Inflation-rate>
- Kumpel, Emily and Kara L. Nelson (2013). “Comparing microbial water quality in an intermittent and continuous piped water supply” *Water Research*. Retrieved from <https://www.sciencedirect.com/science/article/pii/S0043135413004909?via%3Dihub>
- OHCHR (2010). *Right to Water*. Retrieved from <http://www.ohchr.org/Documents/Publications/FactSheet35en.pdf>
- Quigley, Nicholas, Sara G. Beavis and Ian White (2016). “Rainwater harvesting augmentation of domestic water supply in Honiara, Solomon Islands”, *Australasian Journal of Water Resources*. Retrieved from <https://www.tandfonline.com/doi/full/10.1080/13241583.2016.1173314>
- Rossman, Lewis A. (2000). *EPANET Users Manual 2.0*. Retrieved from <http://www.innovyze.com/products/epanet/download/P1007WWU.pdf>
- Vanuatu Government Department of Meteorology and Geo-Hazards et al. (2011). “Current and Future Climate of Vanuatu”. Retrieved from https://www.pacificclimatechangescience.org/wp-content/uploads/2013/06/15_PCCSP_Vanuatu_8pp.pdf
- Wenner, Jennifer M. (2018). “Population Growth and Resource Depletion”, Science Resource Education Center at Carleton College. Retrieved from <https://serc.carleton.edu/quantskills/methods/quantlit/popgrowth.html>
- Wurbs, Ralph A. and Wesley P. James (2014). *Water Resources Engineering*, Pearson Education Inc.
- WHO (2013). “Technical Notes On Drinking-Water, Sanitation And Hygiene In Emergencies”. Retrieved from

http://www.who.int/water_sanitation_health/publications/2011/WHO_TN_09_How_much_water_is_needed.pdf?ua=1

World Bank (2016). “Population growth (annual %)” . Retrieved from <https://data.worldbank.org/indicator/SP.POP.GROW>

UNU-EHS (2015). “Exposed: Why Vanuatu is the world’s most ‘at-risk’ country for natural hazards”. Retrieved from <https://ehs.unu.edu/media/in-the-media/exposed-why-vanuatu-is-the-worlds-most-at-risk-country-for-natural-hazards.html#info>
See also UNU-EHS, *World Risk Report* annually from 2011-2015.

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B Demand Patterns

In order to estimate demand, the population in the villages prior to the 2017 mass evacuation of the island was used whenever possible. In the case of Ambore village, these figures were rounded up to include the daytime water use of government administrators in offices located in the villages. Although only seven staff presently work at the NHC at any given time, these numbers were increased to reflect those of inpatient water users who may be on site. From this, the population growth formula below was used to estimate future user numbers

Equation B.1.

$$P_t = Pe^{rt}$$

where P_t is the final population, P is the initial population, e is the exponential growth term, r is the population growth rate, and t is the period of time (Wenner, 2018). The growth rate used was the World Bank's figure of 2.2%, the time period was 30 years.

Table B.1. Estimated Populations for Demand Model by Location

Location	P	Pt	Pt Rounded
NHC	20	38.69585	39
Nanako	70	135.4355	136
Navitora	110	212.8272	213
Ambore	20	38.69585	39
LJSS	100	193.4792	194

The P_t values were then rounded up to the nearest person; from this point the 20 LCPD demand was converted into GPM and that demand was assigned to its appropriate demand point in the model.

Demand patterns over the course of a day were based on the author's experiences living in the communities and working with the NHC and LJSS.

Figure B.1. Domestic/Household Demand Pattern

Figure B.1 is based on a typical household demand for water. Water is drawn to cook breakfast, wash dishes, do morning cleaning and cook food in preparation for lunch before the sun becomes too hot. Water usage climbs in the afternoon hours, peaking in for the evening bath and boiling water for tea.

Figure B.2. LJSS Demand Pattern

Figure B.2 follows a similar pattern to the household demand pattern, with increased usage throughout the daytime hours due to more washing and cleaning required in a facility with 100 students.

Figure B.3. NHC Demand Pattern

Figure B.3 differs greatly from the other two demand patterns. While health center hours are nationally from 8 AM-5 PM, most patients do not arrive at NHC until dropping their children off around 8:30 or 9 AM. From that point throughout the day, the usage can be quite high as nurse's attend patients, nurse aids clean rooms, and bed linens are washed to hang dry in the hot afternoon sun. Cleaning and sterilization continue until the close of

service. Patients staying overnight often have family members cook on-site and wash dishes in the evening until bed, accounting for after-hours water usage.

These demand patterns were assigned to their respective demand nodes in EPANET. The total demand is multiplied each hour by that node's assigned pattern's multiplier (represented by the bars in the figures) to model the system behavior during that time of day.

C Cost Estimate Analysis

In this section and throughout the report, a rate of 100 Vanuatu Vatu (VUV) is assumed as equivalent to \$1 US. This can vary, but this shorthand commonly used by aid workers as a field equivalent until grants are actually signed and funds requested, when the day's actual rate is applied.

According to Jonathan Toomey, head of Vanuatu Drilling and project manager, the generator powering the pumps uses approximately 1.1 liters of mazut per hour of operation (the price of which is \$4.40 US per liter on West Ambae). Every 100 hours of operation, the oil in the generator must be changed (\$8.40 US per liter in Port Vila). To calculate the amount of mazut or oil used in a year, the number of daily or weekly operating hours were expanded to cover an entire year.

Table C.1. Annual Cost of Mazut and Oil per Daily Operating Time

	MAZUT	OIL
1.71 Hr	\$ 3,012.61	\$ 55.73
4 Hr	\$ 7,047.04	\$ 130.37
5 Hr	\$ 8,808.80	\$ 162.96
11 Hr	\$ 19,379.36	\$ 358.52

The data in Table C.1 summarizes the cost of operating the generator for one year for different amounts of time each day. These prices are in today's dollars.

From this point, the commonly used formula to adjust for inflation was used

Equation C.1.

$$P_n = D * (1 + r)^n$$

where P_n is the price at the end of the inflation term, D is the cost in current dollars, n is the number of years and r is the inflation rate (Department of Public Works, City of Lincoln, NE, 2018). The design life of the project, 30 years, was used as the number of years, and the cost in today's dollars was taken from the table above. It was assumed in this analysis that an inflation gap between the earnings of rural Ni-Vanuatu and the cost of fuel would increase at a rate of 2% per year. . Inflation in Vanuatu in the past years has varied from 0.8% to 4.8% (Knoema, 2018) and investment opportunities in rural Vanuatu can be limited. The past eight years has seen an average inflation rate of 1.66% and median inflation rate of 1.4%. As such, an inflation rate of 2% was judged to be a sufficiently conservative inflation rate for the purposes of this cost estimate analysis.

Inflation was not considered with regard to capital costs in this estimate. Full retail prices currently available in Port Vila, Vanuatu were used in the pricing of the project. These

figures did not include the cost of tooling, transportation, labor, nor the cost of powering generators to run power tools on Ambae to build the project. An example of the prices of wares that would be used to construct the project can be seen below.

Table C.2. Materials and Price List for Full System Expansion

Item	Unit	Unit Price (VUV)	Number	Cost (VUV)
25mm PVC	m	123	1,022	125,706
16mm PVC	m	92	709	65,228
Tap	full unit	5,700	3	17,100
T-joints				
50mm	unit	500	2	1,000
16mm	unit	900	2	1,800
25mm	unit	300	1	300
Cement	20k bag	1,000	65	65,000
Chicken wire	50 m	3,900	3	11,700
Sand	m3	5,000	6	30,000
Gravel	m3	5,000	3	15,000
Reducers				
50mm to 25mm	unit	700	1	700
25mm to 16mm	unit	300	2	600
50mm to 16mm	unit	600	1	600
#18 Wire Tie	kg	800	162	129,600
8mm Rebar	6 m unit	310	245	75,950
Scaffolding	5.8 m unit	100,000	8	800,000
Total				1,340,284

The prices listed in Table C.2 are the retail costs of these items. Contractors will often pay 1/3 to 2/3 of the prices listed above; NGO's will mark up the retail costs approximately 20% as a common practice before submitting a store quotation to a grant application. In Vanuatu at the time of writing, Peace Corps volunteers received a 10% discount at certain hardware stores on project-related purchases.

Shipping in Vanuatu is notoriously variable. On a separate project, the cost of shipping three 6000-L PVC tanks on a five-hour ship transport varied between \$900-\$3000. Rates can vary depending on the season, the size of the ship in relation to the cargo, how the cargo is packaged, the mood of the person quoting the price, whether one has family working on the ship, and how sweetly the person asking the quotation is speaking.

Labor costs were not included in this report for similar reasons. A team of unskilled laborers would be paid approximately \$10 US per person each work day for months; constant supervision would be recommended to ensure quality work. On a large-scale

project such as the one outlined above, flying in a small, well-trained work crew equipped with power tools would cost \$100 US per day, but finish in weeks instead of months. This raises questions of methodology. There are some who believe employing locals builds local capacity, increases community buy-in and goodwill towards the project, and reduces future chances of project vandalism. In some communities, jealousy regarding the increased cash flow into the community might exacerbate existing rivalries. Each organization has its way of operating and it is beyond the scope of this paper to address such topics. As such, the issue of labor and costs have been excluded from the main body of this report.

D EPANET Schematics and Pipe Attributes

The figures below illustrate the systems modeled in EPANET and discussed in this report.

Figure D.1. Schematic of Existing System (Option A)

Figure D.2. Schematic of "Break Between NHC and Nanako" (Option B)

Figure D.3. Schematic of "Break Between Nanako and Navitora" (Option C)

Figure D.4. Schematic of "Break Between Navitora and Ambore" (Option D)

Figure D.5. Schematic of "Break Between Ambore and LJSS" (Option E)

Figure D.6. Schematic of "Fully Connected" System (Option F)

The original water system shown in Figure D.1 was installed using 50 mm PVC pipe. In designing the network expansion, 50 mm pipe was initially used. The pipe diameter between each section was reduced, one by one, checking energy costs with each change. The costs would reduce as flow within the pipes became less turbulent and less energy was wasted. The energy costs would start to rise if the pipes became too narrow and the pumps would need to increase energy usage to overcome the increased friction. Using this method, the sizing of the original network piping did not change, but none of the newly installed piping reached so great a diameter.

Table D.1. Pipe Locations and Attributes

Pipe Linking	Pipe Diameter (mm)	Length (ft)
Borehole 1 to NHC Outlet	50	140
NHC Outlet to NHC Tank	50	15
NHC Outlet to Nanako Outlet	25	1430
Nanako Outlet to Nanako Tank	16	15
Nanako Outlet to Navitora Outlet	25	1920
Navitora Outlet to Navitora Tank	16	15
Navitora Outlet to Ambore Outlet	16	960
Ambore Outlet to Ambore Tank	16	15
Ambore Outlet to LJSS Outlet	16	1320
LJSS Outlet to LJSS Tank	50	15
LJSS Outlet to Borehole 2	50	310

The pipes in used in the design are all PVC with a Hazen-Williams roughness value of 150 (Wurbs and James, 2014). In designing alternative configurations without redundancy (Options B-E), sections of pipe joining outlets were removed with the rest remaining the same. The listing of the pipes in Table D.1 gives the attributes of these pipes in all six configurations; the “breaks” in Options B-E indicate which pipe was omitted from the design.

E EPANET Inputs

In addition to the EPANET inputs already provided (the demand volumes and patterns found in Appendix B and the schematics and pipe attributes found in Appendix D), this section includes information regarding other inputs in the EPANET system design.

Table E.1. EPANET Elevations

Item	Elevation (Feet)
Water Level - NHC Borehole	20.9
NHC Tap	91
NHC Tank	129
Nanako Tap	124
Nanako Tank	163
Navitora Tap	95
Navitora Tank	111
Ambore Tap	79
Ambore Tank	95
LJSS Tap	82
LJSS Tank	112
Water Level - LJSS Borehole	5.2

Table E.1. details the elevations of the junctions/nodes (referred to as “taps” in the table), the tanks, and the two reservoirs. These are also the elevations for their respective connecting pipes as detailed in Table D.1.

The tanks at Ndui Ndui Health Center and Londua Junior Secondary School are both 20 feet tall and 50 feet in diameter. The tanks at Nanako, Navitora, and Ambore villages are all 20 feet tall and 11 feet in diameter. All five water tanks have initial water levels of 20 feet at the start of simulation.

Table E.2. Pump Curve

Pump Curve Input	
Head (Ft)	Flow (GPM)
203.41	0.00
200.13	2.64
196.85	5.28
190.29	7.93
183.72	10.57
177.16	13.21
160.76	15.85
137.79	18.49
111.55	21.14
82.02	23.78
42.65	26.42

The two groundwater pumps installed in West Ambae are identical 3.5” x R4 Leo submersible groundwater pumps. The pump curve used in the simulations is outlined in Table E.2. This pump curve was obtained and can be found at fluidsnz.co.nz, official regional distributor of the pump.

In Options B-F, the following Rule-Based Controls were applied to simulate the pumps turning on and off according to low water levels in the tanks.

RULE 1

IF TANK HC LEVEL ABOVE 19.5
THEN PUMP 12 STATUS IS CLOSED

RULE 2

IF TANK HC LEVEL BELOW 8
THEN PUMP 12 STATUS IS OPEN

RULE 3

IF TANK Londua LEVEL ABOVE 19.5
THEN PUMP 13 STATUS IS CLOSED

RULE 4

IF TANK Londua LEVEL BELOW 8
THEN PUMP 13 STATUS IS OPEN