2021

# CASE STUDY OF GRAVITY-FED MOUNTAIN SPRING TAP SYSTEM IN HA LERONTI, LESOTHO, AFRICA

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Recommended Citation
Peterson, Sarah, "CASE STUDY OF GRAVITY-FED MOUNTAIN SPRING TAP SYSTEM IN HA LERONTI, LESOTHO, AFRICA", Open Access Master's Report, Michigan Technological University, 2021.
https://doi.org/10.37099/mtu.dc.etdr/1217

# CASE STUDY OF GRAVITY-FED MOUNTAIN SPRING TAP SYSTEM IN HA LERONTI, LESOTHO, AFRICA

By

Sarah Peterson

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Civil Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2021

This report has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Civil Engineering.

Department of Civil and Environmental Engineering

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## Acknowledgments

Throughout my research, I have been supported by many to whom I would like to extend my heartfelt gratitude. I would first like to thank my advisor, Dr. Brian Barkdoll, for his abundant encouragement, understanding, and knowledge which helped me navigate my Peace Corps service and research. An additional thanks to my advisory committee, Dr. Kari Henquinet and Dr. David Watkins, for their guidance and patience through the writing process.

I would like to offer my sincere appreciation for my Basotho friends and colleagues who answered my never-ending inquiries about their culture and water security; especially to my good friend, Rocky, who translated my countless questions to those who had answers. He relentlessly worked to get me answers both when I was in Lesotho and after I returned to the United States. Additionally, I would like to thank both my RPCV friends and Peace Corps Lesotho Staff who cheered me along as I tried to juggle my Peace Corps service and obtaining my master's.

Thank you to my loving family; I have been fortunate to be blessed with many families, my parents and sister, my fiancé's family, and the Maichu family, who all supported me through the mountain peaks and valleys of my Peace Corps service. I would like to express my deepest gratitude to my fiancé, Tim, who has been my IT guy and sounding board, and most importantly, my unwavering partner throughout my service and research.

Lastly, I would like to dedicate this project to my host mother, Mme 'Mamohaila, my host father, Ntate Mofokeng, my host grandmother, Nkhono 'Masekoala, my host brother, Abuti Mohaila, and my host sisters, Ausi 'Matsepa and Ausi Mabasotho. They always made sure my rain barrel never went dry, even through the driest of winters.

# Acronyms and Abbreviations

| | |
|---|---|
| DISC | Data and Information Services Center |
| GES | Goddard Earth Sciences |
| LHDA | Lesotho Highlands Development Authority |
| LHWP | Lesotho Highlands Water Project |
| LMICs | Lower Middle-Income Countries |
| LSL | Lesotho Maloti |
| MGC | Matekane Group of Companies |
| NASA | National Aeronautics and Space Administration |
| USD | United States Dollar |

## Cultural Definitions

| | |
|---|---|
| Abuti | A respectful term to address a younger boy; directly translates to brother |
| Ausi | A respectful term to address a younger girl; directly translates to sister |
| Basotho | The people from Lesotho, plural |
| Basutoland | The British protectorate established from 1884 to 1966 in present-day Lesotho |
| Mme | A respectful title to address an older woman; directly translates to mother |
| Mosotho | A person from Lesotho, singular |
| Nkhono | A respectful title to address an older woman; directly translates to grandmother |
| Ntate | A respectful title to address an older man; directly translates to father |

## Technical Definitions

| | |
|---|---|
| Basic Drinking Water Services | Drinking water from an improved source, provided collection time is not more than 30 minutes for a round trip. |
| Basic Sanitation Services | Improved sanitation facilities not shared with other households. |
| Improved Sanitation Facilities | Sanitation facilities that include flush/pour flush to piped sewer systems, septic tanks, or pit latrines, ventilated improved pit latrines, composting toilets, or pit latrines with slabs. |
| Improved Water Sources | Water sources such as piped water, boreholes, tube wells, protected dug wells, protected springs, and packaged or delivered water. |

# Abstract

Water security has been declining rapidly in Lesotho, Africa in recent years. Lack of water has led to food insecurity, livestock deaths, and the spread of disease. Rural Basotho depend on rainfall to sustain their livelihoods; however, precipitation variability has recently increased due to climate change. For those who reside in the highlands of Lesotho, mountain springs can be a clean source of water. The tap system in the village of Ha Leronti relies on gravity to distribute water from two mountain springs to the ten village taps and nearby school campus. However, it is incapable of transporting the basic daily water amount that the Lesotho government says every citizen is entitled. The mountain springs alone cannot accommodate both the demands of the village and school campus, except during times with excessive precipitation. Furthermore, even if there was enough water to provide for the demand, the system would be unable to meet it.

This report provides two scenarios in which modifications to the existing tap system are proposed. The scenarios were created with a 10-year design life taking in account the district's population growth. To ensure the system could handle peak demands, it was assumed the school residences are at full capacity, both schools are in session, and a 24-hour event with an attendance of 600 people is occurring at the auditorium. Once the demands of the school campus and village were calculated, the tap system was modeled in EPANET, a water distribution network solver. New pipe diameters were calculated to accommodate both the peak demands of the school campus and the basic daily water amount of 30 liters per person for the village.

Scenario 1 is the ideal solution with pipe diameters ranging from 16 mm to 90 mm. Scenario 2 is a more economical version of Scenario 1, with pipe diameters ranging from 25 mm to 90 mm. Since the existing system is constructed from 25 mm pipes, only the larger pipes would need replacing to modify the current system to fit Scenario 2. Although Scenario 1 is preferred when comparing water velocities and pressures during peak demand, Scenario 2 is feasible if washout valves are installed downstream of the pipes with low water velocities to prevent sediment accumulation. Additionally, valves should be installed upstream of junctions with high pressures to ensure they can be reduced to safe levels. In both scenarios, Pipe 16 should be monitored for damage due to its high water velocity during peak demand. If the pipe deteriorates, it could need replacing before the 10-year design life is complete. However, there is still the question of where to source the additional water to meet the demands for an updated system.

# 1 Introduction

Lesotho is a mountainous country land-locked entirely by South Africa. It is located within the latitudes of 28.5º and 30.7º South and the longitudes of 27º and 29.5º East. Lesotho is unique as “the only country in the world that is entirely situated above 1,000 m in altitude” (Commissioner of Water 2017), earning its nickname as the Kingdom in the Sky. The country is divided into ten districts: Butha-Buthe, Leribe, Berea, Maseru, Mafeteng, Mohale’s Hoek, Quthing, Qacha’s Nek, Mokhotlong, and Thaba-Tseka, and four agro-ecological zones: Lowlands, Foothills, Mountains (or Highlands), and Senqu (Orange) River Valley (Bureau of Statistics 2010). Each district contains one or more of the four agro-ecological zones (Bureau of Statistics 2010), which are determined by climate and elevation (Mekbib 2012). For visualization of Lesotho’s geographic location, district boundaries, and agro-ecological zones, please refer to Figure 1 below (Mekbib 2012).


Figure 1: Lesotho’s Districts and Agro-Ecological Zones
(published with permission from ATPS (Mekbib 2012))

The lowlands have the highest population density of the country, and therefore, is the “most intensively cultivated of all the zones” (Bureau of Statistics 2010). However, the lowlands only comprise 17% of the country by area which increases the strain on Lesotho’s natural resources in this zone (Mekbib 2012). The lowlands elevation ranges from 1,400 to 1,800 m (Moeletsi et al. 2013) and historically receives moderate rainfall that allows for summer and winter cropping (Bureau of Statistics 2010). The foothills elevation varies from 1,800 to 2,000 m (Moeletsi et al. 2013). This zone has a lower population density and rainfall accumulation compared to the lowlands; however, the foothills can also cultivate summer and winter crops (Bureau of Statistics 2010).

The elevation in the mountains reach 3,482 m at Thabana Ntlenyana, which translates to "beautiful little mountain," in the district of Mokhotlong. The mountains are known to have cold and dry winters (Moeletsi et al. 2013), which restricts this zone to only summer cropping (Bureau of Statistics 2010). Although cultivation is limited in the mountains, livestock frequently traverse the mountains in search of grazing land, especially in summer months when cropland is unavailable. The mountains are the largest zone by area; however, it has the lowest population density (Bureau of Statistics 2010). The final zone is a steep valley that follows the Senqu (Orange) River, which flows from east to west across the central and southern districts of Lesotho. The Senqu River Valley has elevations ranging from 1,400 to 1,800 m (Moeletsi et al. 2013) and historically receives the lowest rainfall accumulation of all the zones, especially in the south-west (Bureau of Statistics 2010). Therefore, this zone has the lowest agricultural productivity in the country (Mekbib 2012). Nonetheless, the Senqu River Valley allows for summer and winter cropping, mainly on the valley floor where there is rich soil along the banks of the river (Bureau of Statistics 2010).

Lesotho is a small country with a population of 2 million and spans a total area of 30,350 $km^2$ (Commissioner of Water 2017). However, only 9% of the land is arable, and approximately 40 million tons of soil erodes per year (Mekbib 2012). The loose topsoil in the lowlands and foothills is vulnerable to erosion by wind and water due to over-grazing (Bureau of Statistics 2010), and in the mountains, watersheds create "deep river valleys, gorges, and gullies" that wash the soil downstream (Mekbib 2012). Vegetation can protect the environment from erosion through soil stabilization and water runoff control; however, Lesotho is sparsely forested, with less than 1% of the land being classified as forestry (Mokuku 2004). The limited vegetative cover continues to decrease as indigenous trees and shrubs are eaten by livestock and used for fuel in rural communities (Mokuku 2004), further worsening soil erosion and diminishing arable land (Mekbib 2012).

Lesotho's climate is heavily influenced by both its geographical location and high elevations, which range from 1,400 to 3,482 m (Moeletsi et al. 2013). The climate is described as "continental and temperate with four distinct seasons of summer, autumn, winter and spring" (Mokuku 2004). Lesotho lies within the southern hemisphere. Therefore, the months that correlate with each season are as follows: December, January, and February are the summer months; March, April, and May are the autumn months; June, July, and August are the winter months; and September, October, and November are the spring months. Continental climates have temperatures that vary significantly throughout the year, and temperate climates have moderate annual rainfall, sometimes with drought periods. As a result, the summers are hot and humid, while winters are typically dry and cold (Moeletsi et al. 2013), and between the months of October and April, Lesotho receives 85% of its annual rainfall (Mokuku 2004).

Although Lesotho's "climate is classified as temperate, it is [only] marginally suitable for crop farming due to erratic and spatially variable rainfall" (Moeletsi et al. 2013). At times, the Senqu River Valley may only accumulate 500 mm of annual precipitation, while the

Drakensburg Mountains, in north-east Mokhotlong, may accumulate over twice that amount, up to 1,200 mm of annual precipitation (Mokuku 2004). Rainfall variability has only worsened with climate change and as a result, increased the recurrence of droughts and floods. Most often, Lesotho experiences agricultural droughts in which there is a lack of rainfall that inhibits typical economic activities, such as agriculture. This is especially problematic as 71% of the population's livelihoods rely, at least partially, on agricultural activities (World Bank 2019).

Excessive precipitation can be just as destructive to crops as droughts; damage from hailstorms or floods can severely reduce the agricultural production for an entire year. In recent years, floods have intensified due to the continual decline of vegetation and degradation of wetlands. Mountain wetlands serve as the headwaters for the major rivers of Lesotho, but when livestock traverse the mountains in search of grazing land they frequently trample and destroy these ecosystems. As a result, many wetlands are losing their ability to purify, store, and regulate the flow of water (Mokuku 2004). When wetlands can no longer provide stream flow regulation, heavy rainfalls can easily turn into flash floods, which often damage crops. Overall, agriculture is typically unproductive due to the climatic variability and limited arable land. Nonetheless, it is still a primary economic sector and the foundation of the Lesotho's economy, even though agriculture has historically "been contributing less to the GDP than any other sector" (Mokuku 2004).

Despite cultivation being unprofitable in Lesotho, most rural communities depend on the environment to survive, often through subsistence farming (or agriculture) (Mokuku 2004). Subsistence agriculture typically only feeds the individuals and families who are actively working the land, meaning there is rarely a surplus of food to sell for profit. Environmental degradation is common where subsistence farming is used due to the use of unsustainable agricultural practices (Mokuku 2004). Nonetheless, subsistence agriculture is a fundamental aspect in Basotho culture because the "land belongs to the nation (*mobu ke oa Sechaba*) and it is the inalienable right of every Mosotho to have access to land, water, pasture, woodland and wildlife" (Mokuku 2004). In a country where land is unrestricted and viewed as communal (Mokuku 2004), it is understandable that Lesotho struggles with land use management.

Low productivity and profits that accompany subsistence agriculture are linked with poverty (World Bank 2019). The added stress of climate change, compounded with Lesotho's environmental degradation, leaves impoverished populations who practice subsistence farming especially susceptible to environmental and economic shocks (Mekbib 2012). Compared to other lower middle-income countries (LMICs), Lesotho's poverty levels are relatively high (World Bank 2019). As of 2017, Lesotho measured its national poverty line at 648.88 LSL per month for one adult (World Bank 2019). This amount translates into 47.69 USD per month according to the 2017 exchange rate, which equates to only 1.57 USD per day (Exchange-Rates.org 2021). Although the poverty levels in Lesotho have been falling in recent years, "economic vulnerability is [still] high, with more than 75 percent of the population either poor or vulnerable to poverty," and almost half of Basotho were officially below the national poverty line (49.7%) in 2017 (World Bank 2019).

High unemployment contributes to Lesotho's prevalent poverty crisis. In 2017, more than a quarter of working-age Basotho were unemployed (28.0%) with youth, ages 15 to 24, having even higher unemployment rates (43.2%). The country's unemployment dilemma is worsened by its weak private sector which limits employment opportunities. The government is the largest formal employer in the country; however, expansion in this sector is unlikely, hindering job creation (World Bank 2019). Therefore, many Basotho are forced to rely on informal jobs which are typically temporary, leaving them vulnerable to poverty.

Further complicating the poverty crisis is the HIV/AIDS epidemic. Globally, Lesotho is the second highest country for HIV prevalence. In 2014, nearly half of all deaths in Lesotho (41.4%) were attributed to HIV/AIDS, and the national life expectancy of 50 years is 18 years less than the average in LMICs (World Bank 2019). Consequently, Lesotho's workforce and productivity has diminished (World Bank 2019), while the dependency on the employed has grown (Mokuku 2004). Children are frequently orphaned due to the spread of HIV, which places further financial burdens on already impoverished communities. As a result, the HIV/AIDS epidemic is considered "the biggest threat to social and economic development in Lesotho" (Mokuku 2004).

While the poverty rates have been recently decreasing, the divide between urban and rural populations continues to widen with the poverty rate skewed higher for rural communities (60.7%) than urban (28.5%) (World Bank 2019). If the environment in Lesotho continues to rapidly deteriorate, the poverty levels in urban communities might improve, but the levels in rural areas will continue to stagnate or potentially worsen. The poverty rates for each district in Lesotho are displayed in Figure 2 below; Maseru, the capital's district, had the lowest poverty levels while the districts, Mokhotlong and Thaba-Tseka, situated in mountains, were the most impacted by poverty (World Bank 2019).

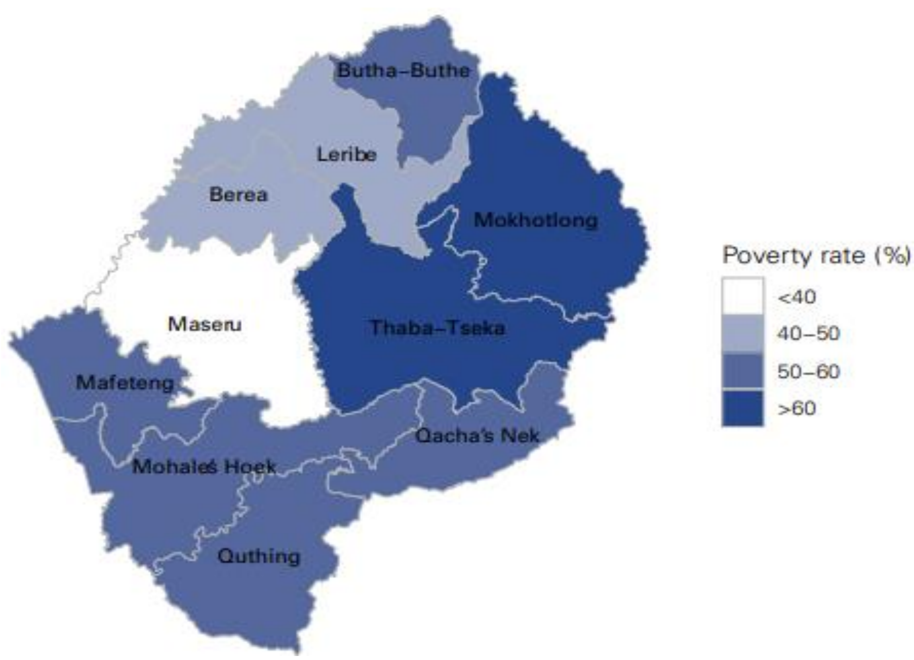


Figure 2: Lesotho Poverty Rate by District
(World Bank 2019)

The relationship between environment and poverty is cyclical; the higher the prevalence of poverty, the more communities rely on their environment to survive, and as their environment deteriorates, communities become poorer because the environment can no longer sustain their livelihoods (Mokuku 2004). Therefore, enforcing environmental protections and adopting sustainable agricultural practices would assist in lowering Lesotho's poverty rate, as an improved environment would reduce the environmental shocks that often keep rural populations poor (World Bank 2019). Another key aspect in poverty alleviation is providing access to basic necessities, such as improved water sources, sanitation facilities, and electricity (Mokuku 2004). Compared to other LMICs, Lesotho is trailing in supplying access to these basic services. The percentage of populations in Lesotho and other countries who had access to basic services in 2000 and 2015 are shown in Figure 3 below.

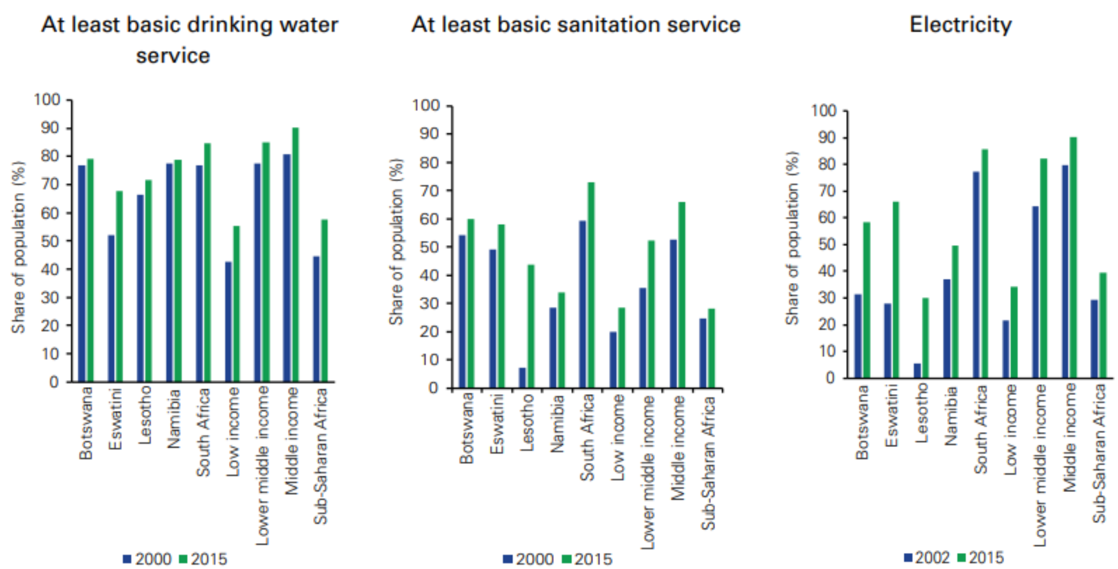


Figure 3: Percentage of Population with Access to Basic Services Compared to Other Countries in the Years 2000 and 2015
(World Bank 2019)

Access to these basic services increased in Lesotho between the years 2000 and 2015; however, improvement to the access of basic drinking water service was minimal compared to other services. Furthermore, coverage in rural areas has lagged due to "reduced investments, climate change, and declining yields or drying up water sources" (World Bank 2019). The government of Lesotho upholds a basic water use policy that states "every Mosotho is entitled to [a] basic daily water amount of 30 liters per day" (Commissioner of Water 2017); nonetheless, 1 in 10 Basotho still do not have access to improved sources of drinking water, most often collecting water from unprotected springs (UNICEF 2019). Those most likely to be without access to improved water sources live in the foothills (25.5%) and mountains (20.6%). As for sanitation, 1 in 4 Basotho do not have access to improved sanitation facilities, most often relying on open defecation. Again, those most likely to be without access to improved sanitation facilities live in the foothills (47.4%) and mountains (46.5%) (UNICEF 2019). Without improved water sources or sanitation facilities, the probability of contracting water borne diseases drastically increases (Mokuku 2004), which only further burdens impoverished populations. Clearly, a prominent divide exists between urban and rural areas regarding access of basic services, a divide which only prevents rural populations from escaping poverty. The percentage of Basotho who had access to basic services in 2017 according to their region is displayed in Figure 4 below.

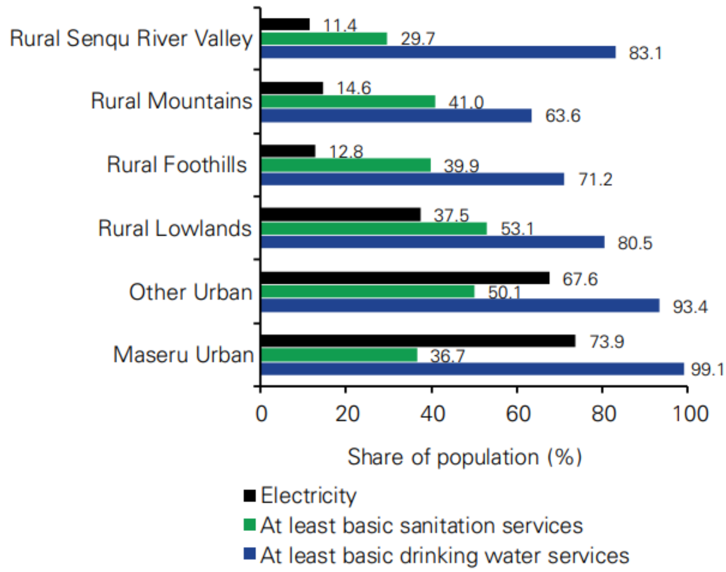


Figure 4: Percentage of Lesotho's Population with Access to Basic Services by Region in 2017
(World Bank 2019)

Despite 1 in 10 Basotho not having access to improved water sources, water is the only natural resource Lesotho has in abundance. Before Lesotho gained independence, the High Commissioner to Lesotho (then known as Basutoland), Sir Evelyn Baring, had the water potential of Basutoland surveyed, laying plans forward for the exportation of water to South Africa. These plans were originally rejected in the 1950s by South Africa; however, after droughts in the mid-1960s, the project was revived. After conducting feasibility studies, the Treaty of the Lesotho Highlands Water Project was signed on October 24, 1986 (Lesotho Highlands Development Authority 2021a). The Lesotho Highlands Water Project (LHWP) is an ongoing, multi-phase project that consists of constructing a system of dams and tunnels in Lesotho to pipe water to the Gauteng province of South Africa. In addition to the exportation of water, LHWP also generates electricity for Lesotho and funds community-based programs for rural Basotho (Mokuku 2004). The Lesotho Highlands Development Authority (LHDA) manages the ongoing construction and maintenance for LHWP within Lesotho's borders. Currently, Phase I is complete and construction is underway for Phase II.

In Phase I, three dams were built: Katse Dam, 'Muela Dam, and Mohale Dam. The Katse and Mohale Dams were built in the Thaba-Tseka district, while 'Muela Dam was built in the Butha-Buthe district. Katse Dam was completed in May 1997 and water delivery to South Africa began in January 1998. Currently, Katse Dam is the largest, with a reservoir volume of 1,950 million $m^3$. Figure 5 below shows the reservoir above Katse dam during the summer of 2018.

Figure 5: Photo of Katse Reservoir taken January 2018
(photo by author)

Alongside the construction of Katse Dam was ‘Muela Dam, which generates electricity for Lesotho. Prior to ‘Muela Dam’s construction, Lesotho was entirely dependent on South Africa for electricity. At the end of Phase I, Mohale Dam was completed in April 2002. Mohale Dam is approximately half the size of Katse Dam, with a reservoir volume of 946.9 million $m^3$. Including its interconnecting transfer tunnel, Mohale Dam was built to be a backup reservoir to ensure that LHWP could accommodate for “South Africa’s ever-increasing demand” (Lesotho Highlands Development Authority 2021b). Phase II is currently under construction, but its plans include a second backup reservoir to be built in the Mokhotlong district. Polihali Dam is expected to be larger than Katse Dam with a reservoir volume of 2,325 million $m^3$. Much like the construction of Mohale Dam, Phase II construction will also include a transfer tunnel to connect Polihali Dam to Katse Dam (Lesotho Highlands Development Authority 2021c). Figure 6 shows a map of Lesotho with LHWP’s current and planned construction for Phases I and II.

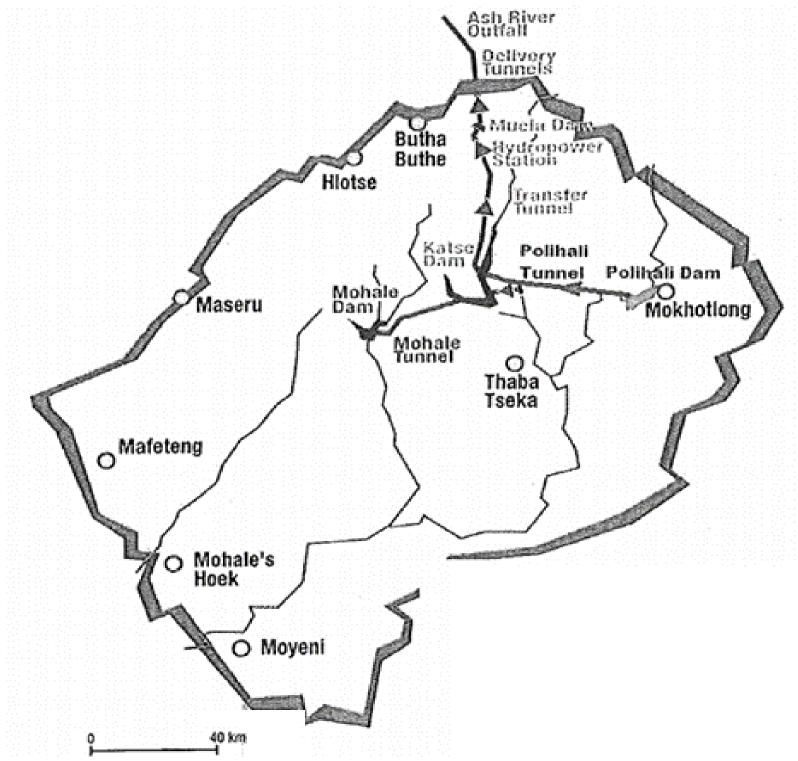


Figure 6: Phase I and II Lesotho Highland Water Project Map
(Kingdom of Lesotho et al. 2011)

In the LHWP treaty signed in 1986, annual minimum water quantities were agreed upon. The water deliveries were to begin in 1995 with a minimum amount of 57 million $m^3$. The projected amounts increased each year, ending with the years following 2020 at a minimum of 2,208 million $m^3$ per year (Kingdom of Lesotho et al. 1986). Nevertheless, these minimums have not been strictly followed due to delays in construction. On August 11, 2011, the agreement on Phase II of LHWP was signed, and the annual minimum quantities of water were renegotiated. Instead of delivering a minimum of 2,208 million $m^3$ of water in 2021, Lesotho was projected to export 927 million $m^3$. This agreement projected minimums until the year 2044, with a minimum water delivery of 1,245 million $m^3$ per year (Kingdom of Lesotho et al. 2011). Compared to the 1986 treaty, the minimums agreed upon in 2011 were just over half the amount that was expected at the completion of LHWP in 1986. However, the planned water deliveries have since stagnated at 780 million $m^3$ per year until Polihali Dam is complete (Lesotho Highlands Development Authority 2021c).

According to LHDA annual reports, the dam levels are heavily dependent on the precipitation accumulation that the highlands receive throughout the year. Beginning in May 2011, the LHDA observed a negative trend in the total storage of the reservoir system (Lesotho Highlands Development Authority 2016). Aside from nominal fluctuations, LHWP has thus far been able to meet South Africa's increasing water demands. However, precipitation variability in the region has intensified due to climate change, and therefore, also increased the recurrence of droughts. With a significant portion of Lesotho's annual precipitation reserved for South Africa's consumption, Basotho have less water security, especially during recent severe droughts.

Although LHWP has benefited Lesotho's economy through job creation, electricity generation, and water royalties, it has also displaced rural Basotho and negatively impacted the ecosystems in the highlands of Lesotho. To mitigate these issues, the LHDA developed social and environmental programs which include relocating affected communities, compensating individuals for project related losses, and environmental resource conservation and monitoring (Lesotho Highlands Development Authority 2021b). However, demand for water has rapidly grown throughout the region as the "investment into water resources development has made water a costly resource" (Mokuku 2004). A combination of the increased demand in Lesotho and the exportation of vast quantities of water to South Africa could have international ramifications for other countries downstream (Mokuku 2004). This could result in water shortages in Namibia or Botswana, the two countries furthest downstream of the Senqu (Orange) River Basin.

Lesotho has seen a shift in annual precipitation in recent years. According to data collected by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC) satellite, annual area-averaged precipitation since 2001 has ranged from a low of 545 mm in 2015 to a high of 1,137 mm in 2006. Most recently in 2019, the area-averaged precipitation in Lesotho was only 669 mm (Huffman et al. 2019). Figure 7 below displays Lesotho's annual precipitation accumulation for the years 2001 to 2019 with a negatively sloped linear regression, which shows that although the precipitation levels vary each year, the overall annual precipitation levels are declining.

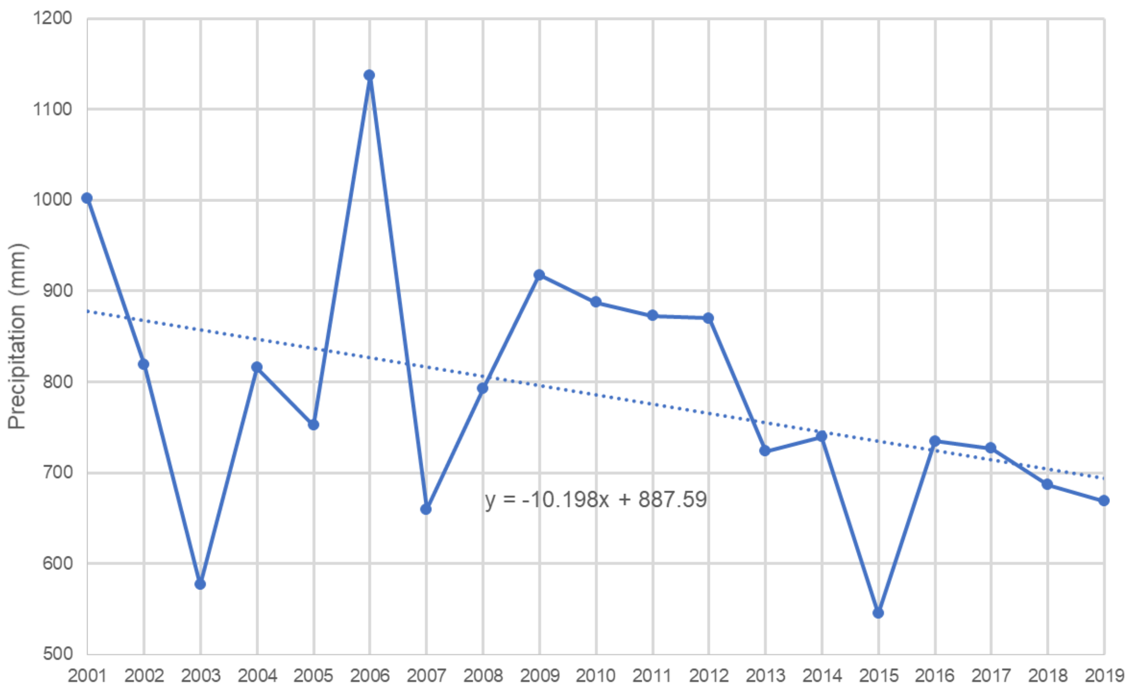


Figure 7: Annual Area-Averaged Precipitation in Lesotho
(data sourced: (Huffman et al. 2019), graph created by author)

In addition to the annual precipitation levels decreasing, the peak times of precipitation are shifting from late spring and early summer to mid-summer and early autumn. Historical data assessments from 1961 to 1994 forecast that climate change will bring a decline of precipitation in the spring and summer months, while the autumn and winter months will bring an increase (Mekbib 2012). This deviation "brings a shift in [sowing] and harvesting seasons to which unexpected disastrous situations could happen before crops [are] harvested in the field" (Mekbib 2012). The lowlands, foothills, and Senqu River Valley may be able to adjust their agricultural practices to accommodate later harvests, but, due to frost in the mountains, the highlands are at the mercy of climate change. However, the increase of precipitation in the winter "may suggest an increase [of] activity in frontal systems which may result in heavier snowfall and strong devastating winds [that] often bring disasters and human suffering posing significant risks for agricultural production in Lesotho" which would ultimately affect all Basotho (Mekbib 2012). Figure 8 displays the shift in Lesotho's peak precipitation times throughout the years 2001 and 2019 (Huffman et al. 2019).

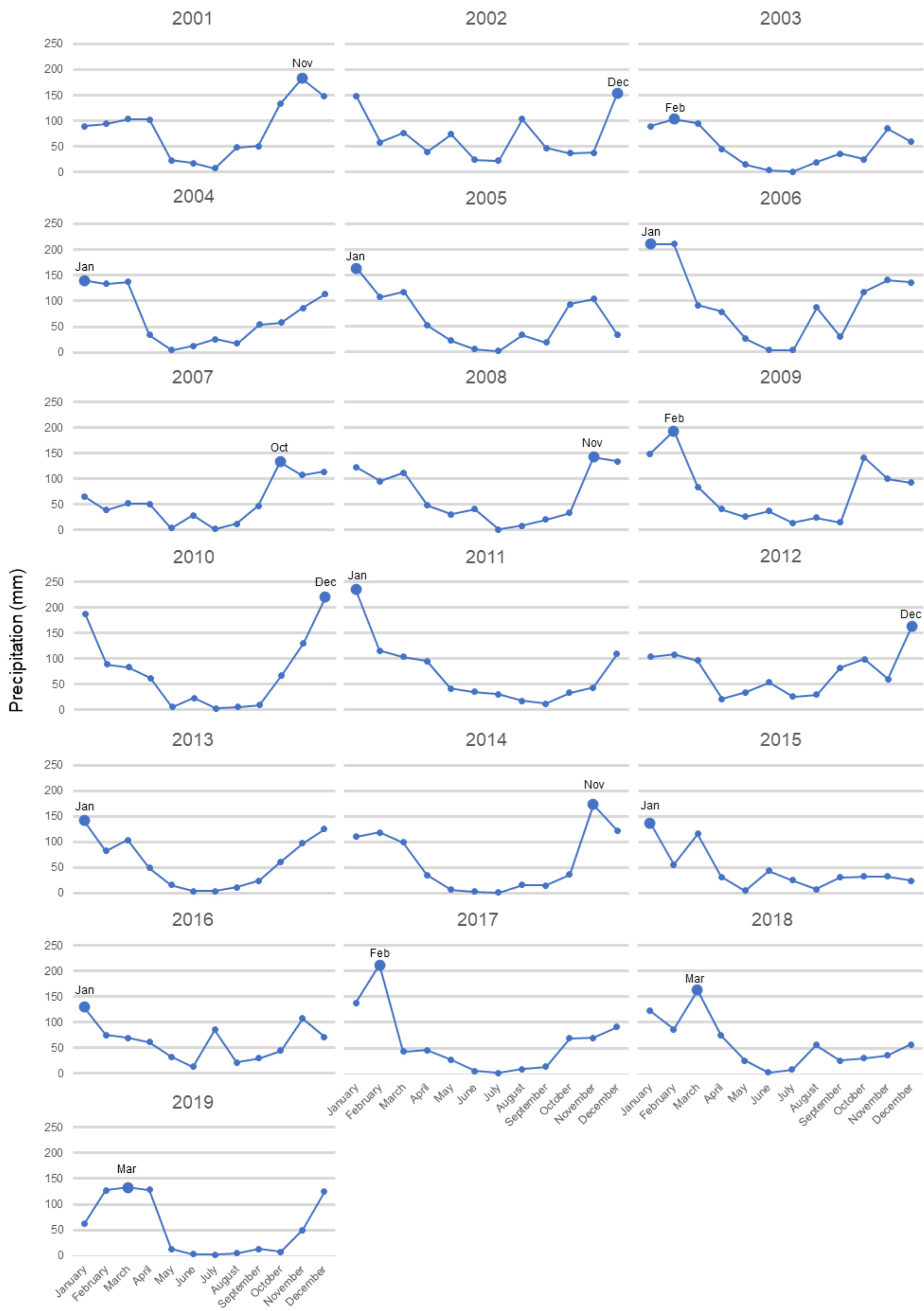


Figure 8: Monthly Area-Averaged Precipitation in Lesotho
(data sourced: (Huffman et al. 2019), graphs created by author)

This case study's site is situated in the mountains of Thaba-Tseka in the village of Ha Leronti. Ha Leronti is one of many villages that comprise the town of Mantsonyane, located approximately 120 km east from the country's capital, Maseru. In recent years, Mantsonyane has received less precipitation than other regions in Lesotho. According to data collected by the NASA GES DISC satellite, the regions that received the most precipitation over the past two decades have been the Drakensburg Mountains in the north-east and the southern tip of Quthing. Conversely, the lowlands in the west and mountains in central Thaba-Tseka have been the driest. Figure 9 below shows the accumulation of precipitation Lesotho has received between the years of 2001 and 2019 (Huffman et al. 2019).

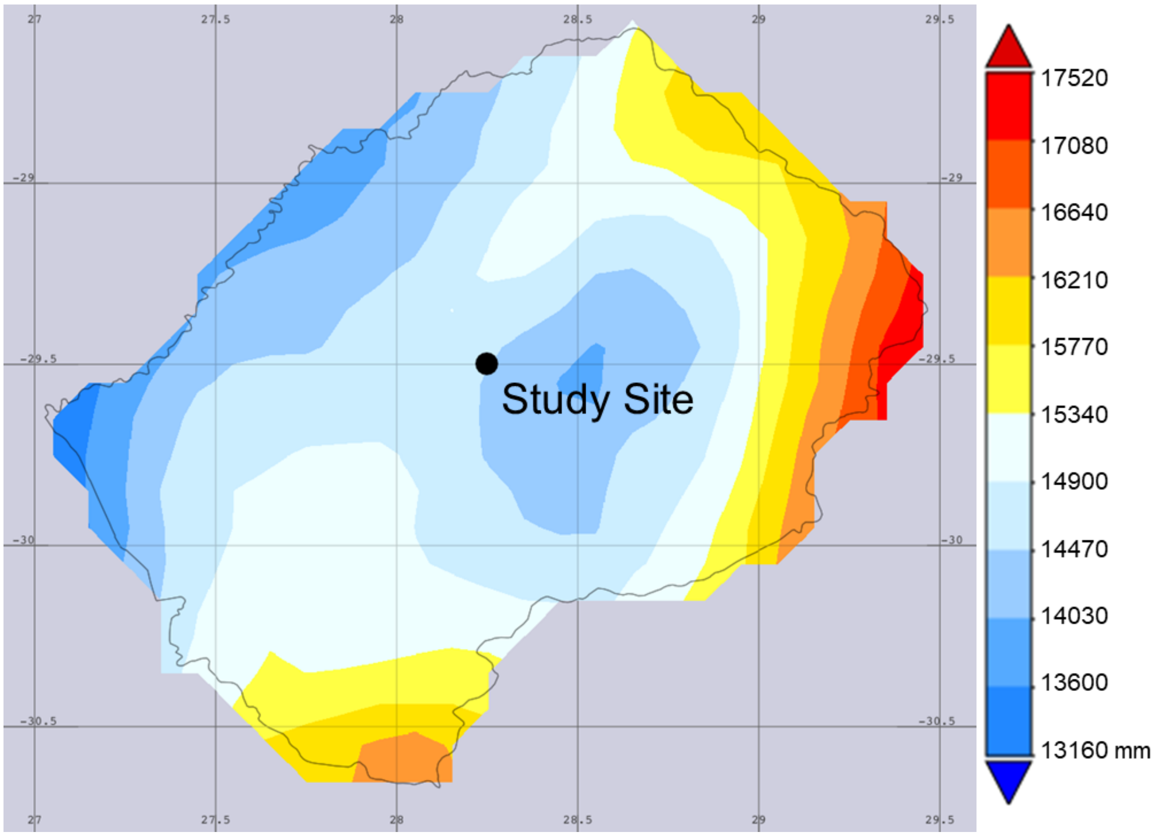


Figure 9: Cumulative Precipitation from 2001 to 2019 Map of Lesotho
(data sourced: (Huffman et al. 2019), map generated by author)

Furthermore, annual precipitation accumulation throughout all of Lesotho has been declining over the past two decades. Therefore, not only is Mantsonyane receiving less precipitation than other regions in Lesotho, but it is also becoming drier with each passing year. Figure 10 displays Lesotho's annual precipitation accumulations for the years 2001 to 2019 (Huffman et al. 2019).

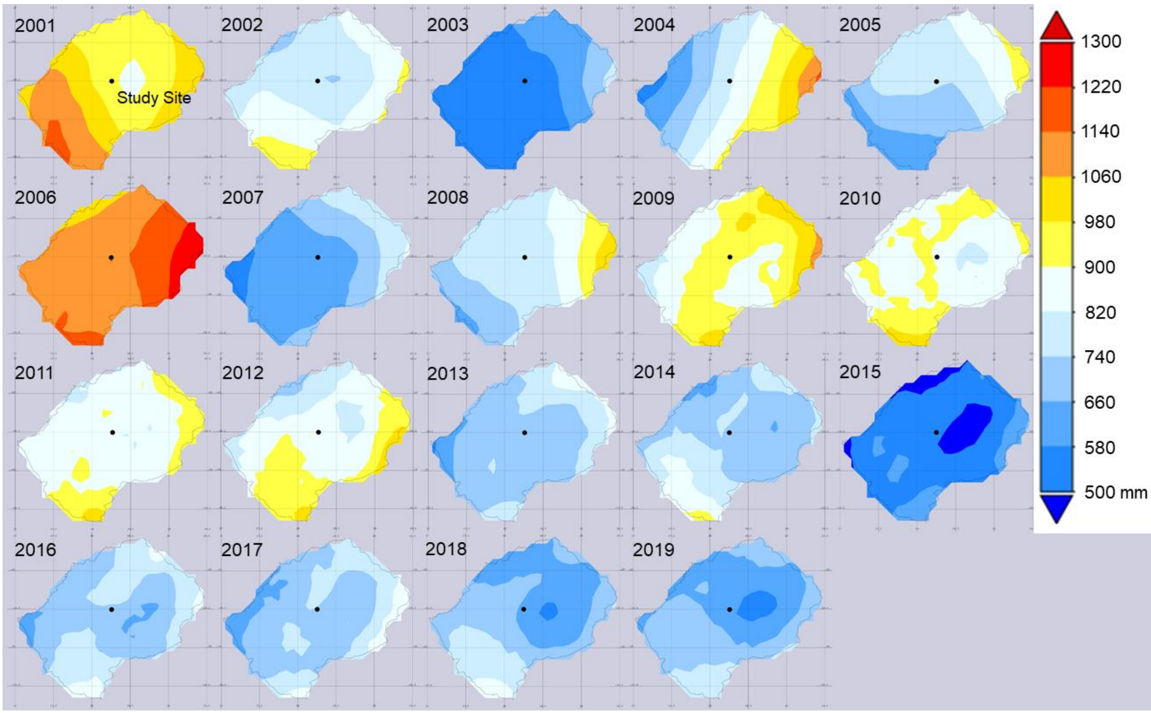


Figure 10: Annual Precipitation Maps of Lesotho
(data sourced: (Huffman et al. 2019), maps generated by author)

The author of this report lived in the village of Ha Leronti for approximately two years from 2018 to 2019 and taught mathematics at the neighboring high school. Throughout her time living in Ha Leronti, she witnessed Basotho struggle daily with water insecurity. She learned the following information through her conversations with local Basotho. In 2018, construction began on a new tap system to serve the school campus and the village of Ha Leronti. Water is drawn from two nearby mountain springs and fills a series of five tanks, made of brick and concrete. Two tanks, with a capacity of 20 $m^3$ each, deliver water to the school campus, while the remaining tanks, with capacities of 20 $m^3$, 7 $m^3$, and 4 $m^3$, deliver water to the village. The system relies on gravity to distribute water to the school buildings and the ten village taps. Examples of a village tank and tap are shown in Figures 11 and 12.

Figure 11: Photo of Village Tank 1 (left) and Old Tank (right) taken September 2019
(photo by author)

Figure 12: Photo of Village Tap 5 taken December 2019
(photo by author)

This new system increases the accessibility of water in the community, as the previous system fell into disrepair nearly a decade before. However, the springs cannot always accommodate both the demands of the village and school due to inconsistent precipitation. Priority is given to the school when the springs' water levels are low because the system was built and paid for by the benefactor of the school, Matekane Group of Companies (MGC). When water is available, the village taps are typically closed every four days to allow the village tanks to recharge. This often results in the women waking before dawn in hopes of procuring water for their families. However, when there has been no recent precipitation, the village taps might be closed for weeks or months at a time. During these desperate times, water is drawn from unimproved sources such as unprotected springs or surface water, and bucket lines, like the one shown in Figure 13 below, will appear at the village taps.

Figure 13: Photo of Bucket Line at Village Tap 2 taken September 2019
(photo by author)

Although this tap system is an improvement, it is still not capable of transporting the basic daily water amount that the Lesotho government says every citizen is entitled (Commissioner of Water 2017). According to information provided by Ntate David, a local government official, the entire system is built from 25 mm PVC pipes. In total, the tap system serves 212 families in Ha Leronti, in addition to those living on the school campus. Even if there were enough water to provide the basic daily water amount for the village and peak demands of the school campus, the existing system would be unable to meet the demand.

# 2 Procedure

After witnessing the challenges local Basotho had with the tap system, the author decided to model the system to properly analyze its shortcomings and determine potential improvements. First, information and data were collected. The author hiked to the most accessible tank in the village, village tank 1, and each village tap to record their GPS coordinates and elevations. The pipeline was followed to each connecting village tap to view all the branches of the system. Throughout the hike, the author attempted to closely follow the pipeline so it would be accurately depicted in the model; however, the pipeline from the old system was unintentionally followed instead. Therefore, in the model, straight lines connect the taps assuming that was how the pipes were laid. The remaining tanks were visually identified from afar since they were not easily accessible by foot or vehicle, and their approximate locations were recorded.

Next, additional information was collected during an informal interview with Ntate David, a local government official. He answered many questions relating to the tap system, including the pipe material and diameter, the approximate location and type of water source, the approximate locations and sizes of tanks, and the number of families who reside in Ha Leronti. In addition, Ntate David verified observed information that had been previously collected during the hike such as the number of tanks and taps, the length of time that the system had been operational, the frequency the taps were open for water collection, and if the system utilized pumps. The data and information collected during the hike and interview were recorded and saved for modeling once the author returned to the United States.

Before creating the model, the tap system was outlined in Google Earth using the recorded GPS coordinates of village tank 1 and the ten village taps. The school buildings and school tanks were visually identified in Google Earth, while the two remaining village tank locations were approximated. Additionally, the GPS coordinates and elevations of the school buildings, school tanks, and village tanks were found using Google Earth. It is important to note that there are multiple school taps on the campus as well. However, the taps are adjacent to the buildings; therefore, the school taps and buildings were merged in the model. The outline of the tap system can be seen in Figure 14.

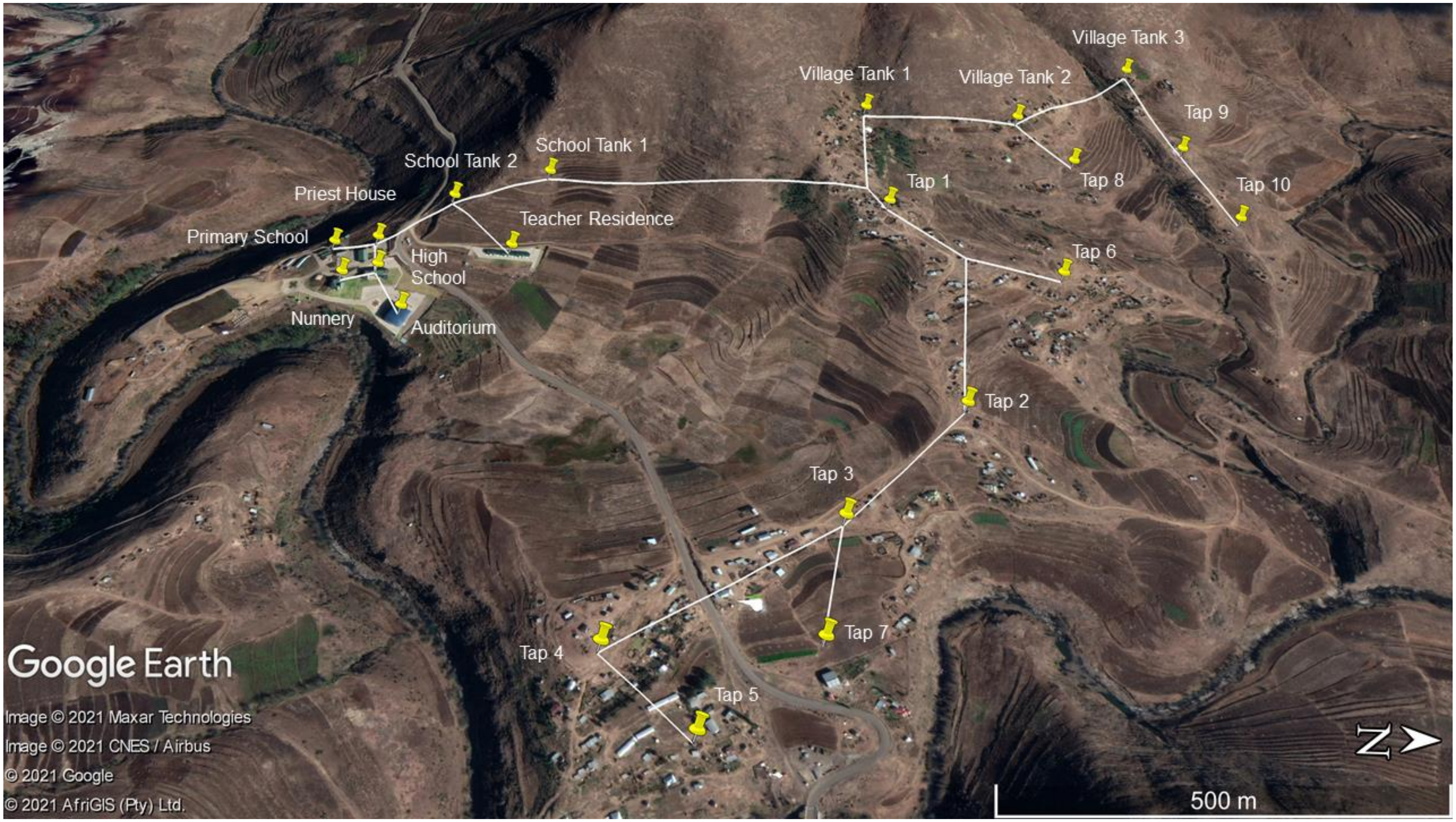


Figure 14: Current Tap System shown in Google Earth
(image created by author)

Next, a rough sketch of the tap system, including all five tanks, the ten village taps, and school buildings, was drawn in EPANET (version 2.0 and build 2.00.12.01). EPANET is a public domain software application that models water distribution systems. It can be used to design and size new systems as well as modify existing systems like the tap system in Ha Leronti. The software and manuals can be found at the United States Environmental Protection Agency's website (USEPA 2020). In this model, village tanks 1 and 2 were classified as reservoirs in EPANET because they supply the water from two nearby mountain springs. Due to this classification, it is important to note that this model assumes that there is an infinite water supply. The following properties were input for each reservoir, tank, pipe, and junction. For both reservoirs, the EPANET model required the total head, which is the ground elevation of the tank with the added height of water (or the height of the tank). For each tank, the ground elevation, initial level of water (assumed to be half the height of the tank), minimum and maximum height of water, and diameter of tank were required. In EPANET, tanks are automatically assumed to be cylindrical, and therefore, the diameter and maximum height of the water indicates the size and the volume of water which it can hold. However, the tanks are not cylindrical but rather cubic with a known volume. Therefore, for the purposes of the EPANET model, the tank diameters (d) were found using the volume (V) and an assumed height (h) using the following equations:

$$V = \pi r^2 h$$
$$d = 2r$$

The dimensions used in the EPANET model for the tank and reservoir properties are shown below in Table 1.

Table 1: Tank Dimensions for EPANET model

| Tank | Actual Volume ($m^3$) | Assumed Height (m) | Calculated Diameter (m) |
|---|---|---|---|
| **School Tanks 1 & 2** | 20 | 2 | 3.57 |
| **Village Tank 1** | 20 | 2 | N/A* |
| **Village Tank 2** | 7 | 1 | N/A* |
| **Village Tank 3** | 4 | 0.5 | 3.19 |

*Not applicable because these tanks are considered reservoirs in EPANET

For each pipe, the diameter, length, and roughness were required. According to information provided by Ntate David, the pipe diameters for the entire system are consistent at 25 mm. The lengths of the pipes were found using the GPS coordinates between the different junctions. In the EPANET hydraulics options, the headloss formula was set to Hazen-Williams; therefore, the roughness was set to 150, which is the Hazen-Williams coefficient for PVC pipes (Wurbs et al. 2002). The junctions in this model are the pipeline splits, village taps, and school buildings. For each junction, the ground elevation and demand were required. Google Earth was used to verify the recorded elevation at each junction. A design life of 10 years with the current population growth in Thaba-Tseka (4.2%) were both considered when determining the water demand of the tap system (Bureau of Statistics 2016). To ensure the system could handle peak demands, this model assumes the school residences (teacher residence, priest house, and nunnery) are at full capacity, the primary school and high school are both in session, and a 24-hour event with an attendance of 600 people is occurring at the auditorium (events that are 24-hours or longer are common in Basotho culture). Additionally, the demand was calculated to meet the basic daily water amount of 30 liters per person for the village.

In this model, the village demand was split evenly between nine of the ten village taps. It was assumed that tap 9 serves only one family due to fencing around the house, encompassing the tap. According to the country's Bureau of Statistics, the average household size in Lesotho is 3.7 people (Bureau of Statistics 2016). However, the author observed that most families in the village spans multiple generations. Therefore, it was calculated that the average family size in Ha Leronti was 7.4 people (7.7 people with population growth) because most families had two houses on their land. Table 2 below shows the demand for each village tap.

Table 2: Demand at Village Taps accounting for Population Growth

| Village Tap Number | Number of Families Served | Number of People Served | Demand (L/d) | Demand (L/s) |
|---|---|---|---|---|
| **1 - 8** | 23.4 | 180.8 | 5423 | 0.0628 |
| **9** | 1.0 | 7.7 | 231 | 0.0027 |
| **10** | 23.4 | 180.8 | 5423 | 0.0628 |

The demand at the school buildings in this model included typical modern water needs. The school campus has flushing toilets which is uncommon for the area. During the author's time teaching at the high school, she observed that there was not enough water for everyone to use the toilets, and therefore, only the teachers and visitors had access. The high school students used the pit latrines downhill from the nunnery instead. However, it was assumed since MGC had built many toilets on campus that they ultimately wanted them to be available to students as well. Therefore, the demand at the schools included drinking water, toilet flushing, and hand washing for both students and teachers. At the school residences, the demand included drinking water, bathing, toilet flushing, and hand washing. For the event held in the auditorium, the demand included toilet flushing and an additional 30 liters per person for activities such as drinking, cooking, or washing. Population growth was only used in calculating the demand at the teacher residence, high school, and primary school since there is limited capacity at the priest house, nunnery, and auditorium. Table 3 below shows the demand at the school campus.

Table 3: Demand at School Buildings accounting for Population Growth

| School Building | Number of People Served | Demand (L/d) | Demand (L/s) |
|---|---|---|---|
| **Teacher Residence** | 23.1 | 4313 | 0.0499 |
| **Priest House** | 1.0 | 186 | 0.0022 |
| **Nunnery** | 15.0 | 2797 | 0.0324 |
| **High School** | 463.7 | 9055 | 0.1092 |
| **Primary School** | 566.8 | 11069 | 0.1335 |
| **Auditorium** | 600.0 | 36168 | 0.4186 |

Next, water use patterns were created for the different junctions because the demands do not remain consistent throughout the day. The junctions were divided into the following water use categories: residential village taps, residential school campus, schools, and auditorium event. The residential village taps pattern includes the ten village taps. The residential school campus pattern includes the teacher residence, priest house, and nunnery. The schools pattern includes both the primary school and high school. The auditorium event only includes the auditorium. Overall, the patterns of the residential village taps, residential school campus, and schools peak during the early morning and late afternoon to early evening. However, the auditorium event pattern remains constant throughout the 24-hour period because Basotho typically do not rest during events. All water use patterns used in the model can be seen in Figure 15 below.

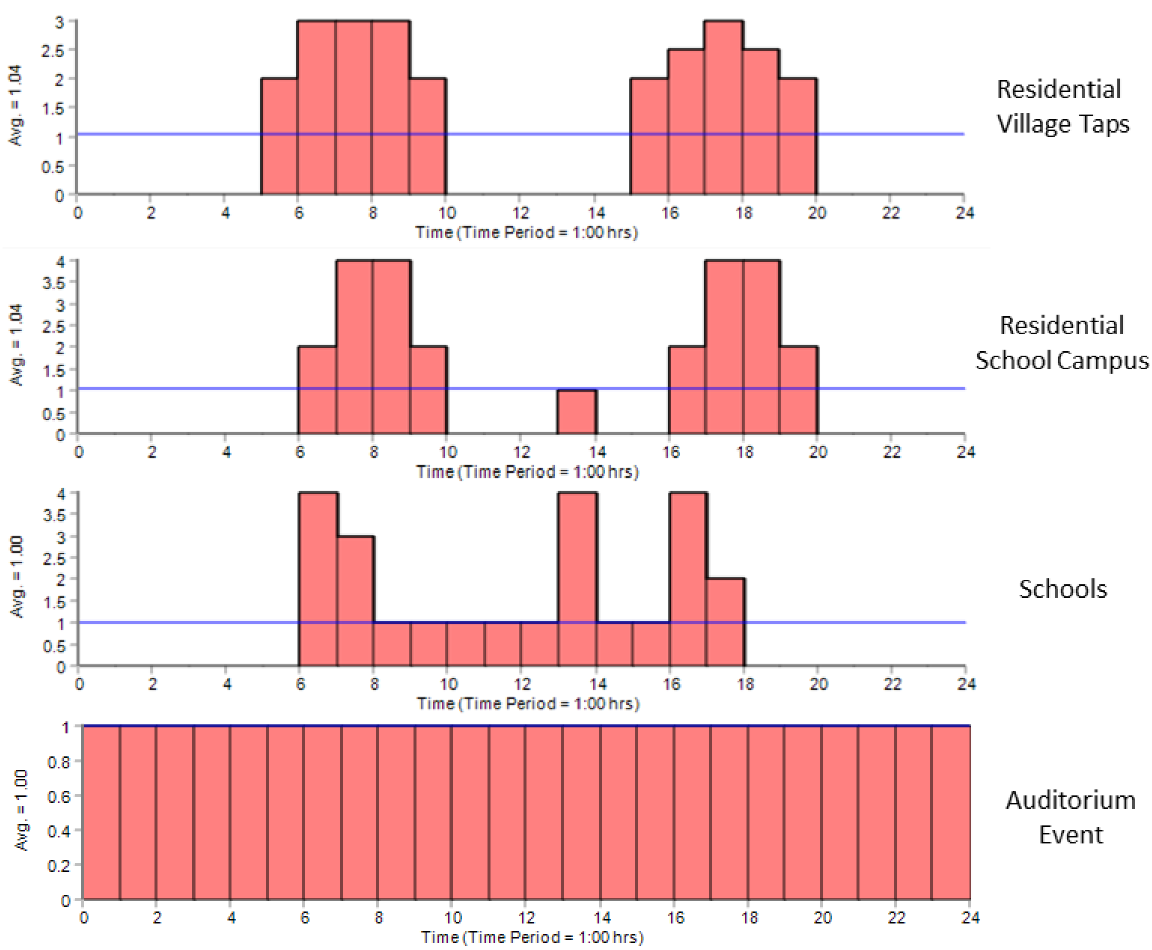


Figure 15: Water Usage Patterns
(image created by author)

Figure 16 displays the current tap system modeled in EPANET with numeric labels for each reservoir, tank, pipe, and junction.

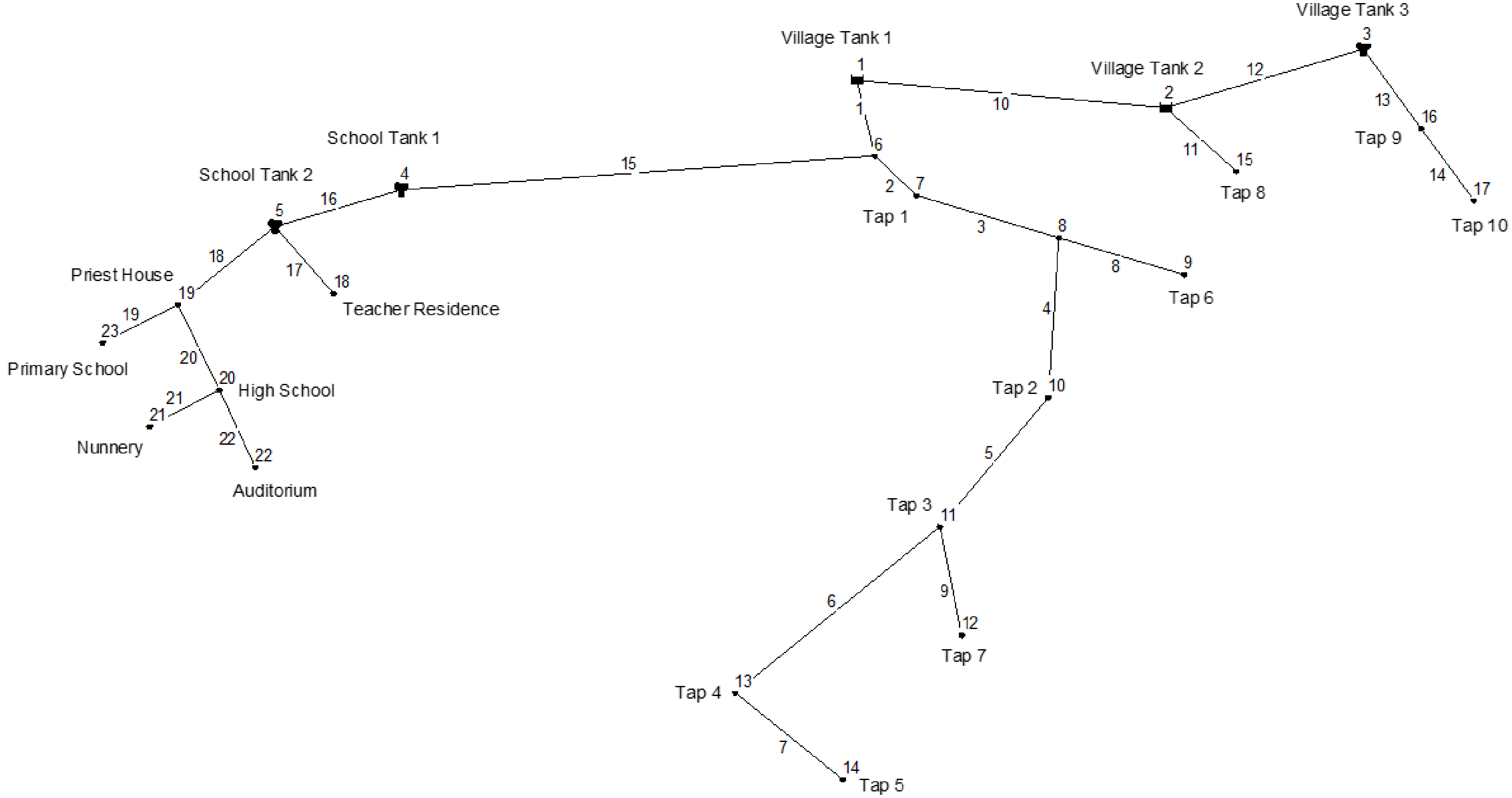


Figure 16: Current Pipe System Modeled in EPANET
(image created by author)

After the required properties were input for each reservoir, tank, pipe, and junction, the EPANET model was run. Many errors were reported for the exisiting system with consistent 25 mm pipes. The reported errors included that the system was unbalanced and disconnected, nodes had disconnected, and negative pressures were present. These errors result from the system's inability to meet the demands. Please refer to Appendix B to view the truncated EPANET status report for the existing system.

The water usage patterns displayed in Figure 15 show the system's peak demand at 7:00 hours. To visualize the reported negative pressures, a network map was created at 7:00 hours that show each junction's pressure. With the exception of tap 8 (junction 15), tap 9 (junction 16), tap 10 (junction 17), and the teacher residence (junction 18), every junction had negative pressures. These negative pressures indicated insufficient flow rates at those junctions. Figure 17 shows the pressure network map. In addition to the pressure network map, a velocity network map at 7:00 hours was created to view the water velocity in each pipe. Velocities below 0.6 m/s can allow sediment accumulation, which can ultimately block pipes (Wurbs et al. 2002). Nearly half of the pipes in the system had water velocities below this threshold at 7:00 hours. Figure 18 shows the velocity network map.

Furthermore, the errors reporting an unbalanced system, disconnected system, and disconnected nodes indicate the existing system with consistent 25 mm pipes cannot meet the peak demands of the school campus and the basic daily water amount of 30 liters per person for the village. Therefore, modifications were made to the pipe diameters (d) in the system. The following equations were used to increase the pipe diameters to accommodate for the demand.

$$Q = VA$$

$$A = \pi r^2$$

$$d = 2r$$

The flow (Q) in each pipe was assumed to be the cumulative demand of all the junctions downstream in the system. Additionally, the velocity (V) of the water was assumed to be 0.6 m/s considering the water would ideally flow at a rate that would not allow for sediment accumulation. After the diameters were calculated for each pipe, they were rounded up to the next commercially available size. Figure 19 shows these diameters.

The EPANET model was then rerun with the modified pipe diameters. Once again, errors were reported that indicated the modified system could not meet the peak demands; however, there were considerably less warnings for this model than the previous model. Please refer to Appendix C to view the truncated EPANET status report for the modified system. Using trial and error, the pipe diameters were increased incrementally to the next commercially available pipe diameters until the EPANET model ran without error.

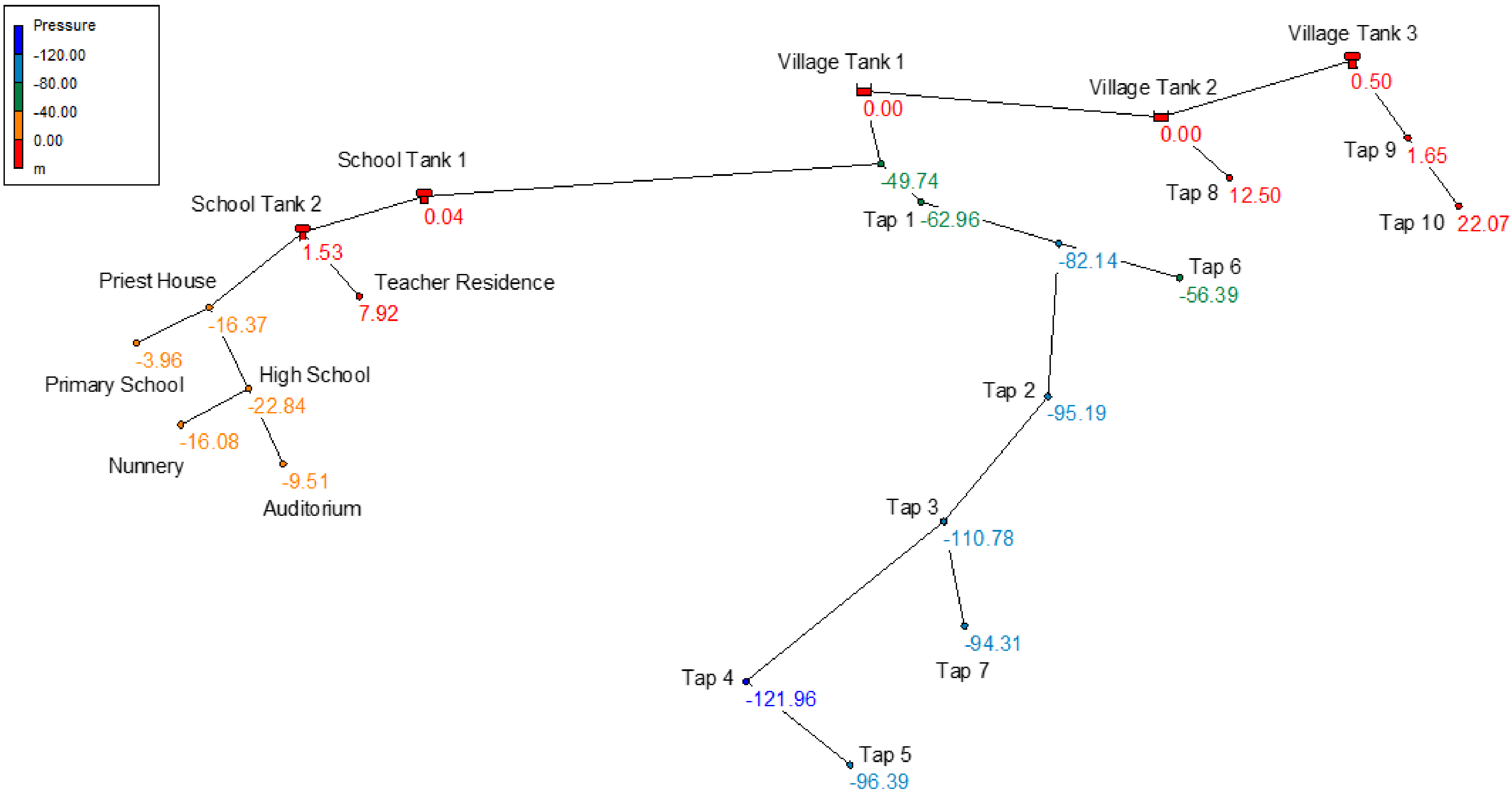


Figure 17: Current Pipe System Pressures at 7:00 hours
(image created by author)

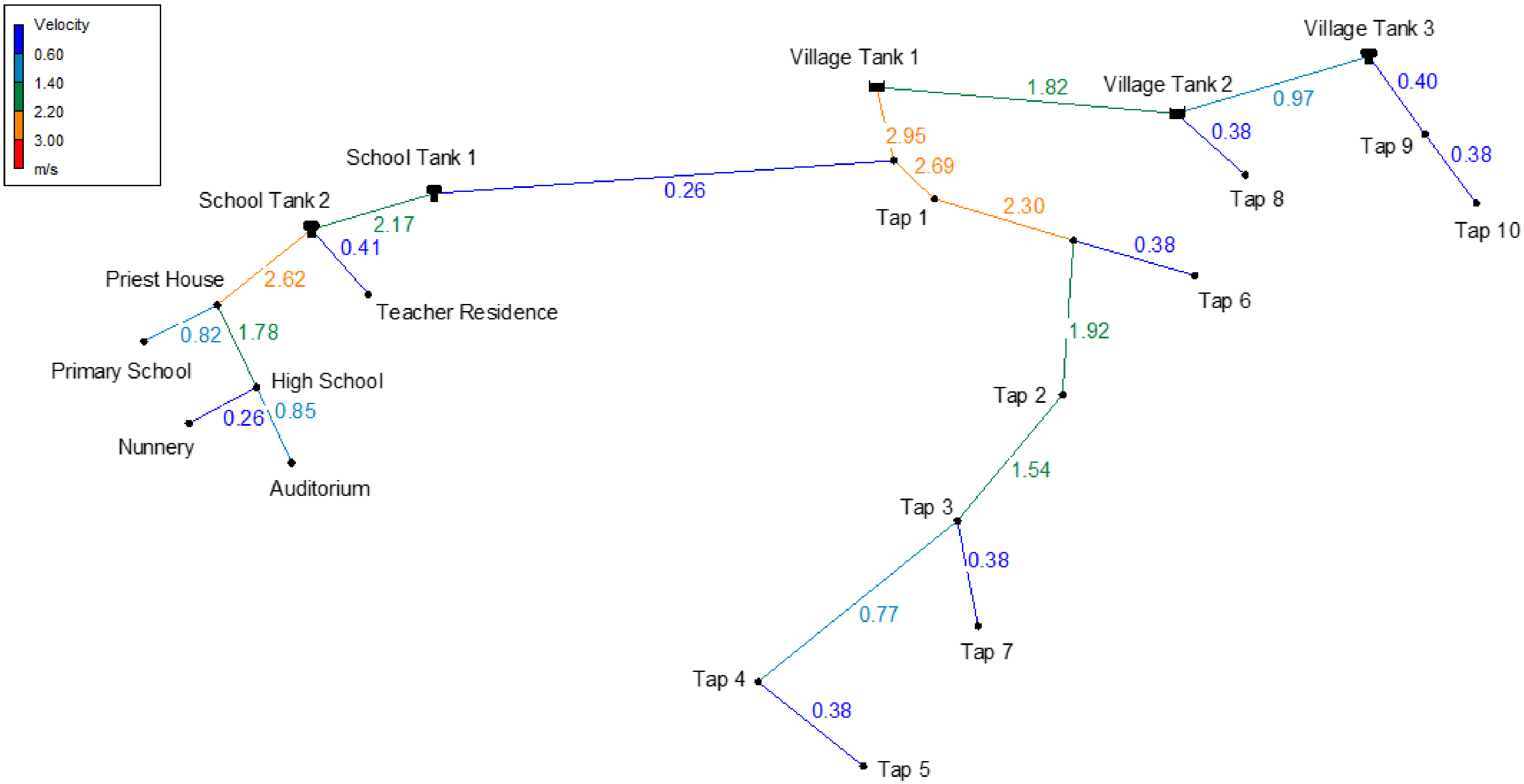


Figure 18: Current Pipe System Velocities at 7:00 hours
(image created by author)

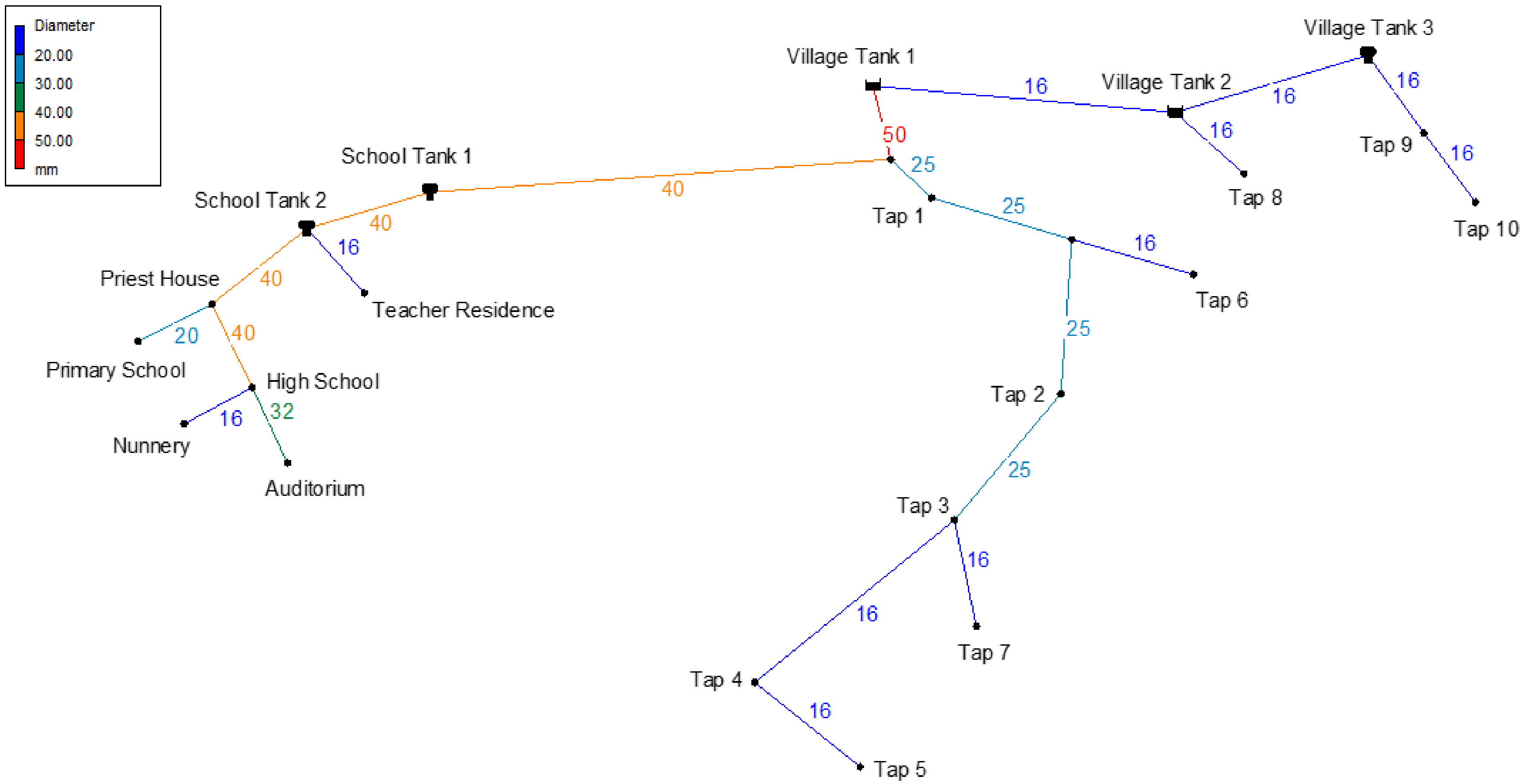


Figure 19: Pipe Diameters with Initial Modifications
(image created by author)

# 3 Results

Two potential solutions were found to meet both the peak demands of the school campus and the basic daily water amount of 30 liters per person for the village. Scenario 1 is the ideal solution which includes pipe diameters ranging from 16 mm to 90 mm. Figure 20 shows this scenario's proposed pipe diameters. During the peak demand at 7:00 hours, the pressures at each junction are all positive which indicate sufficient flow rates at all school buildings and village taps. However, tap 9 (junction 16) and the teacher residence (junction 18) have pressures below 10 m, which is the preferred minimum water pressure for rural water system designs (Arnalich 2010). Additionally, tap 2 (junction 10), tap 5 (junction 14), and tap 6 (junction 9) have high pressures at peak demand that should be reduced by partially closing a valve upstream. For extra precaution, valves should be installed upstream of every village tap and school building to ensure pressures can be adjusted to safe levels. Figure 21 shows each junction's pressure at 7:00 hours.

In Scenario 1, it is important to note there are water velocities lower than the 0.6 m/s threshold at peak demand. This indicates the possibility for blocked pipes (Wurbs et al. 2002). The pipes in question are between the following junctions: tap 3 and tap 4 (pipe 6), village tank 2 and tap 8 (pipe 11), village tank 3 and tap 9 (pipe 13), and school tank 2 and the teacher residence (pipe 17). To ensure these pipes do not become blocked by sediment, washout valves should be installed downstream of these pipes at the village taps 4, 8, and 9, and the teacher residence. Ideally, washout valves should be installed at every village tap and school building. Conversely, the pipe between the school tanks (pipe 16) exceeds the maximum water velocity in pipe systems, 3 m/s. These high velocities can damage the pipes and reduce their longevity (Wurbs et al. 2002). Therefore, Pipe 16 may need to be replaced before the 10-year design life is complete. Figure 22 shows the water velocities in each pipe at 7:00 hours.

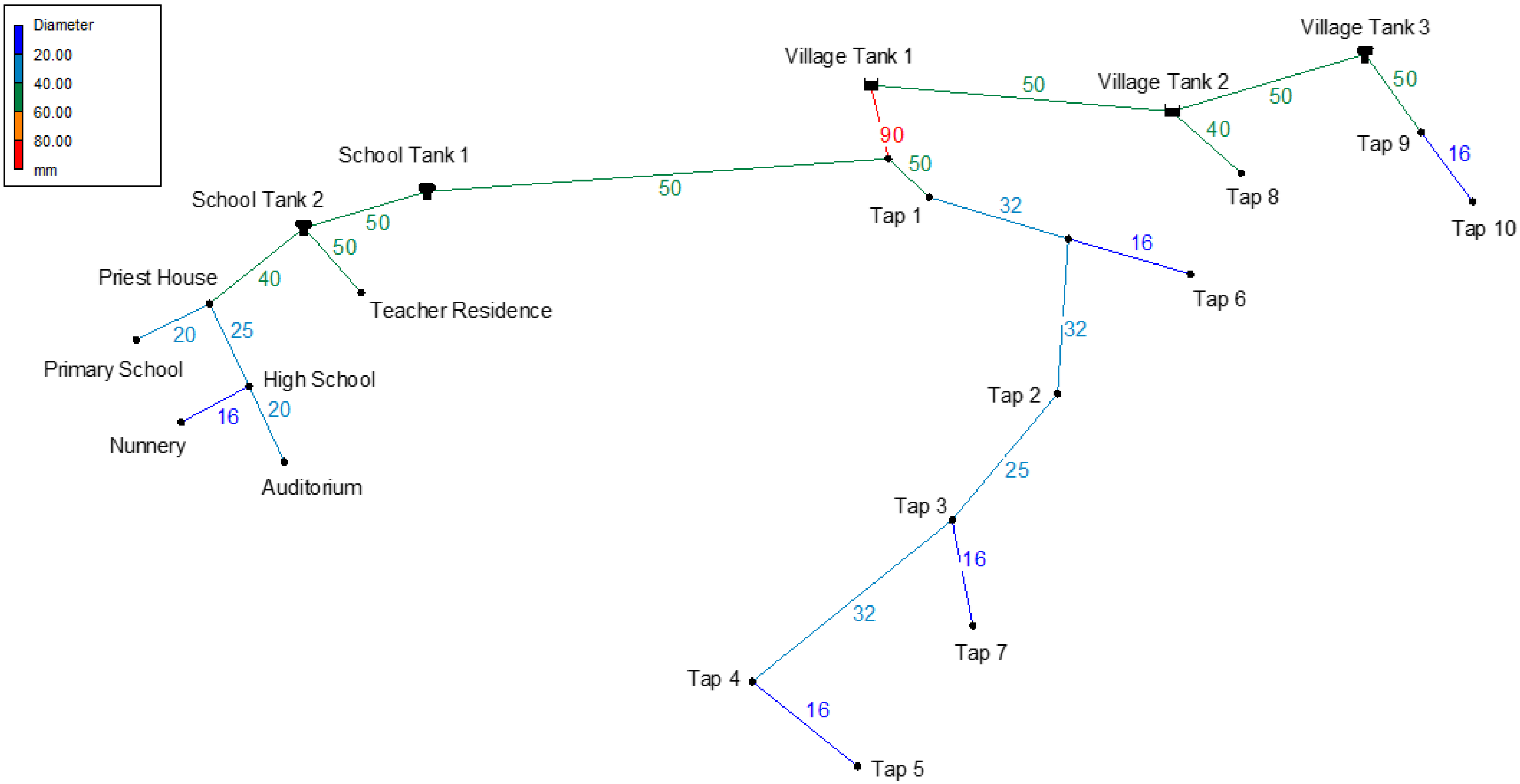


Figure 20: Scenario 1 Pipe Diameters
(image created by author)

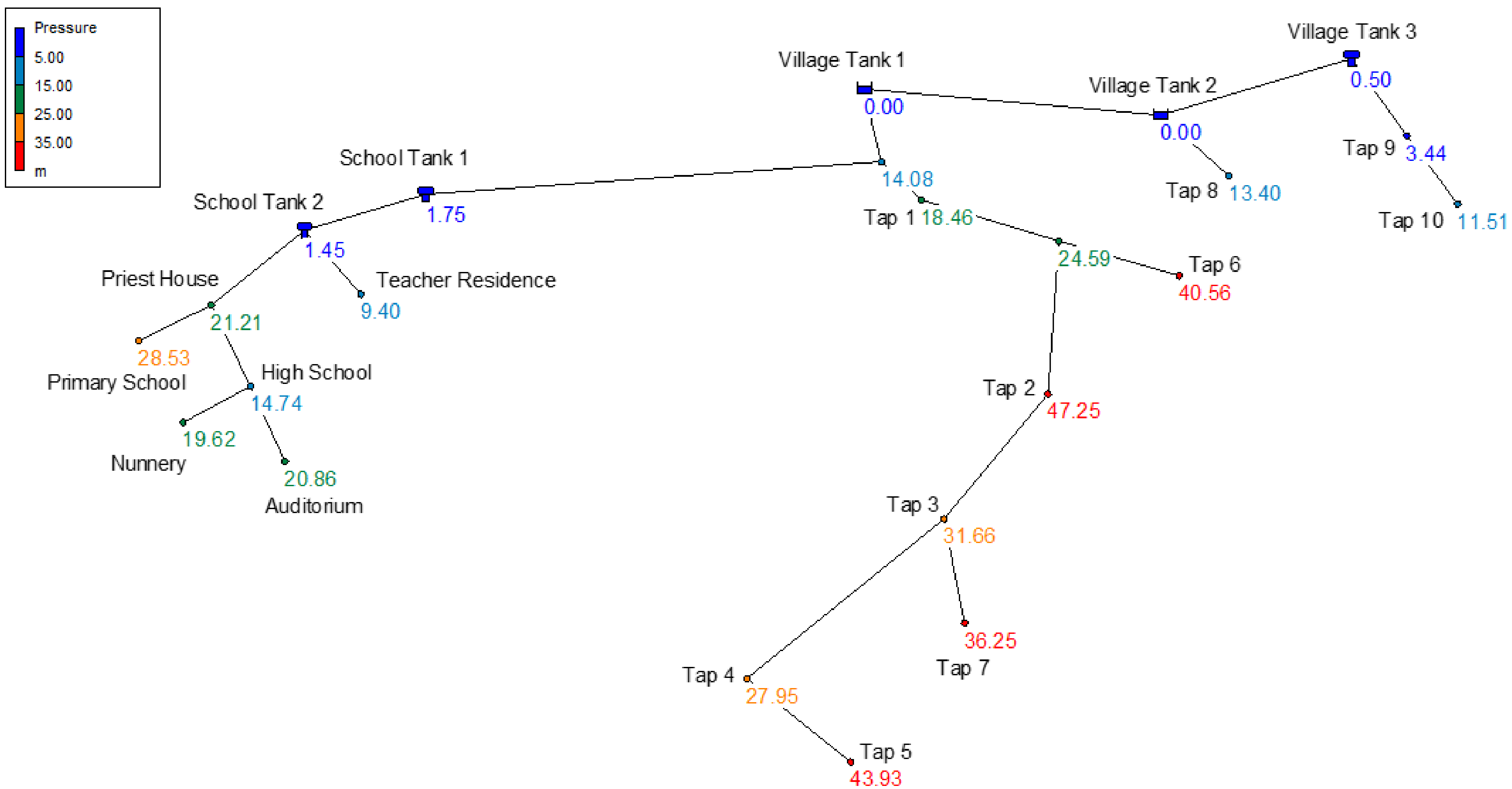


Figure 21: Scenario 1 Pipe System Pressures at 7:00 hours
(image created by author)

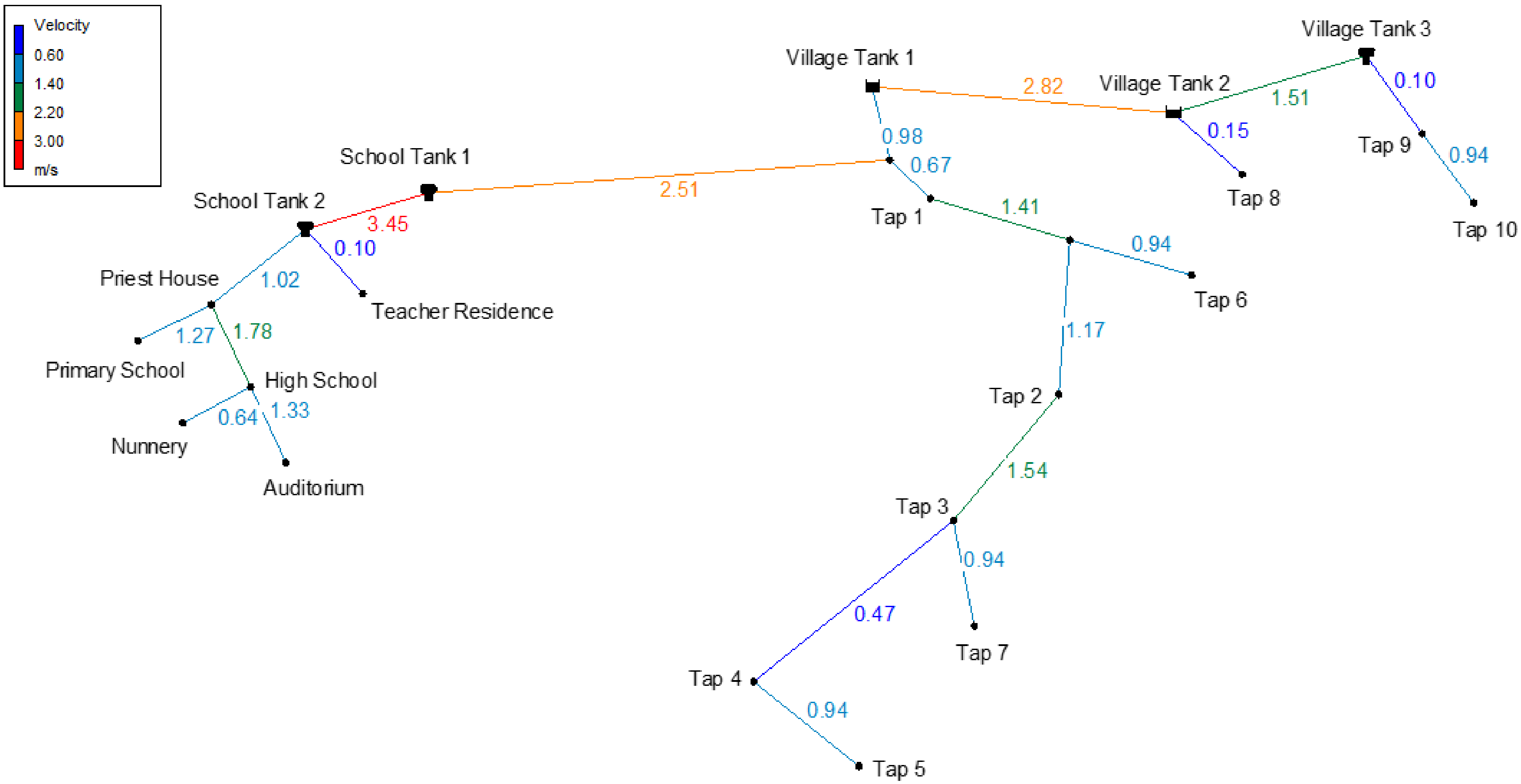


Figure 22: Scenario 1 Pipe System Velocities at 7:00 hours
(image created by author)

Scenario 2 is a modified version of Scenario 1, in which the pipe diameters range from 25 mm to 90 mm. This scenario was created to be a more economical version of Scenario 1. Since the existing tap system is comprised of 25 mm pipes, it would be more cost-effective to replace only the pipes with sizes greater than 25 mm. Figure 23 shows the proposed pipe diameters for Scenario 2. Like Scenario 1, the pressures at each junction for Scenario 2 are all positive during the peak demand, which indicate sufficient flow rates at all school buildings and village taps. However, tap 9 (junction 16) and the teacher residence (junction 18) have pressures below 10 m, which is the preferred minimum water pressure for rural water system designs (Arnalich 2010). In addition, tap 2 (junction 10), tap 5 (junction 14), tap 6 (junction 9), and tap 7 (junction 12) have high pressures at peak demand that should be reduced by partially closing a valve upstream. Ideally, valves should be installed upstream of every village tap and school building to ensure pressures can be adjusted to safe levels. Figure 24 shows each junction's pressure at 7:00 hours for Scenario 2.

Considering the minimum pipe diameter has increased from 16 mm to 25 mm in this scenario, the water velocities are slower. Therefore, more pipes could possibly be blocked by sediment. The pipes in question are between the following junctions: tap 3 and tap 4 (pipe 6), tap 4 and tap 5 (pipe 7), the second pipe split and tap 6 (pipe 8), tap 3 and tap 7 (pipe 9), village tank 2 and tap 8 (pipe 11), village tank 3 and tap 9 (pipe 13), tap 9 and tap 10 (pipe 14), school tank 2 and the teacher residence (pipe 17), and the high school and the nunnery (pipe 21). To ensure these pipes do not become blocked by sediment, washout valves should be installed downstream of these pipes at the village taps 4-10, the teacher residence, and the nunnery. As stated previously in Scenario 1, washout valves should be installed at every village tap and school building for extra precaution. Additionally, in this scenario, the pipe between the school tanks (pipe 16) exceeds the maximum water velocity in pipe systems, 3 m/s. Pipe 16 should be closely monitored in case replacement is needed before the 10-year design life is complete. Figure 25 shows the water velocities in each pipe at 7:00 hours for Scenario 2.

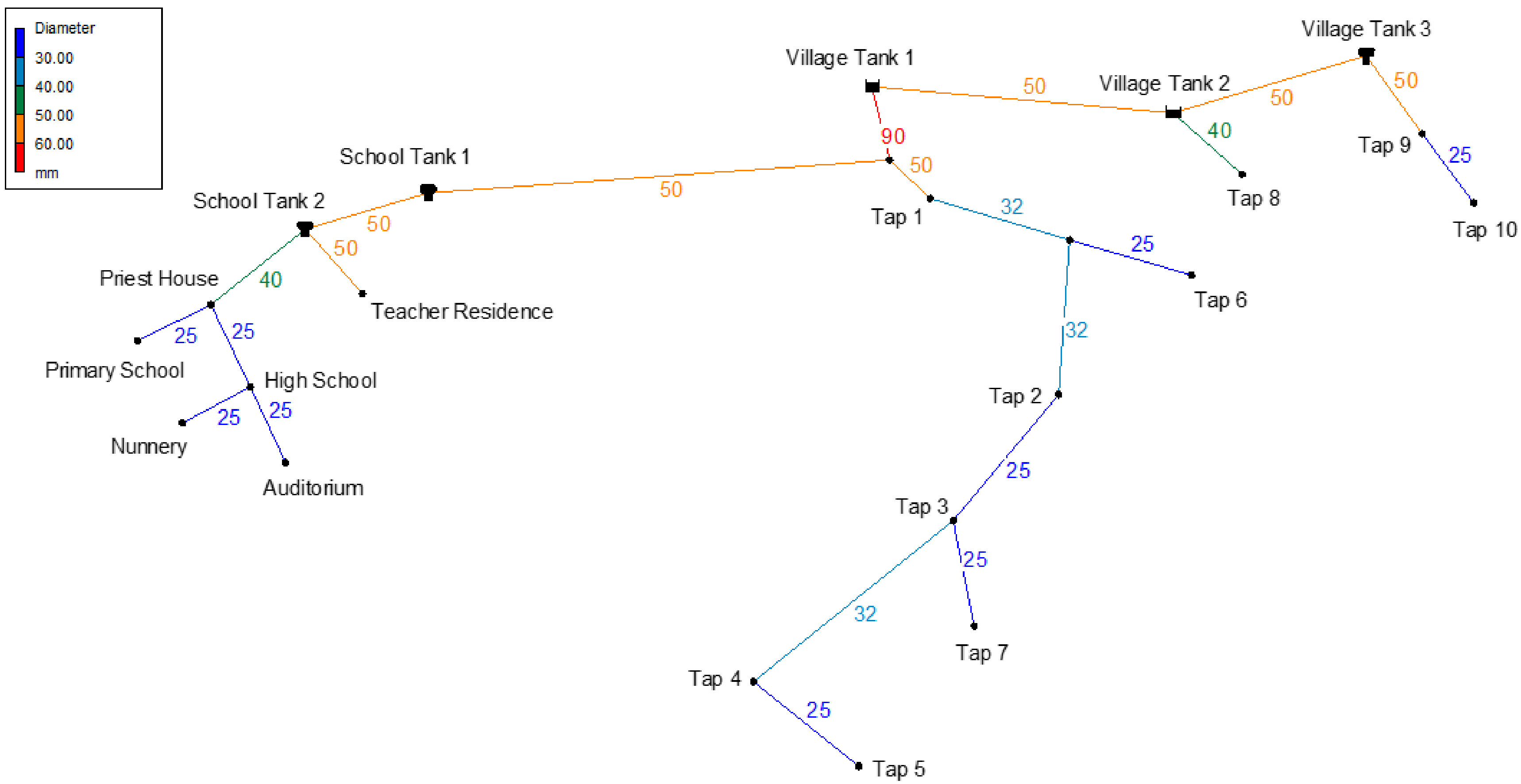


Figure 23: Scenario 2 Pipe Diameters
(image created by author)

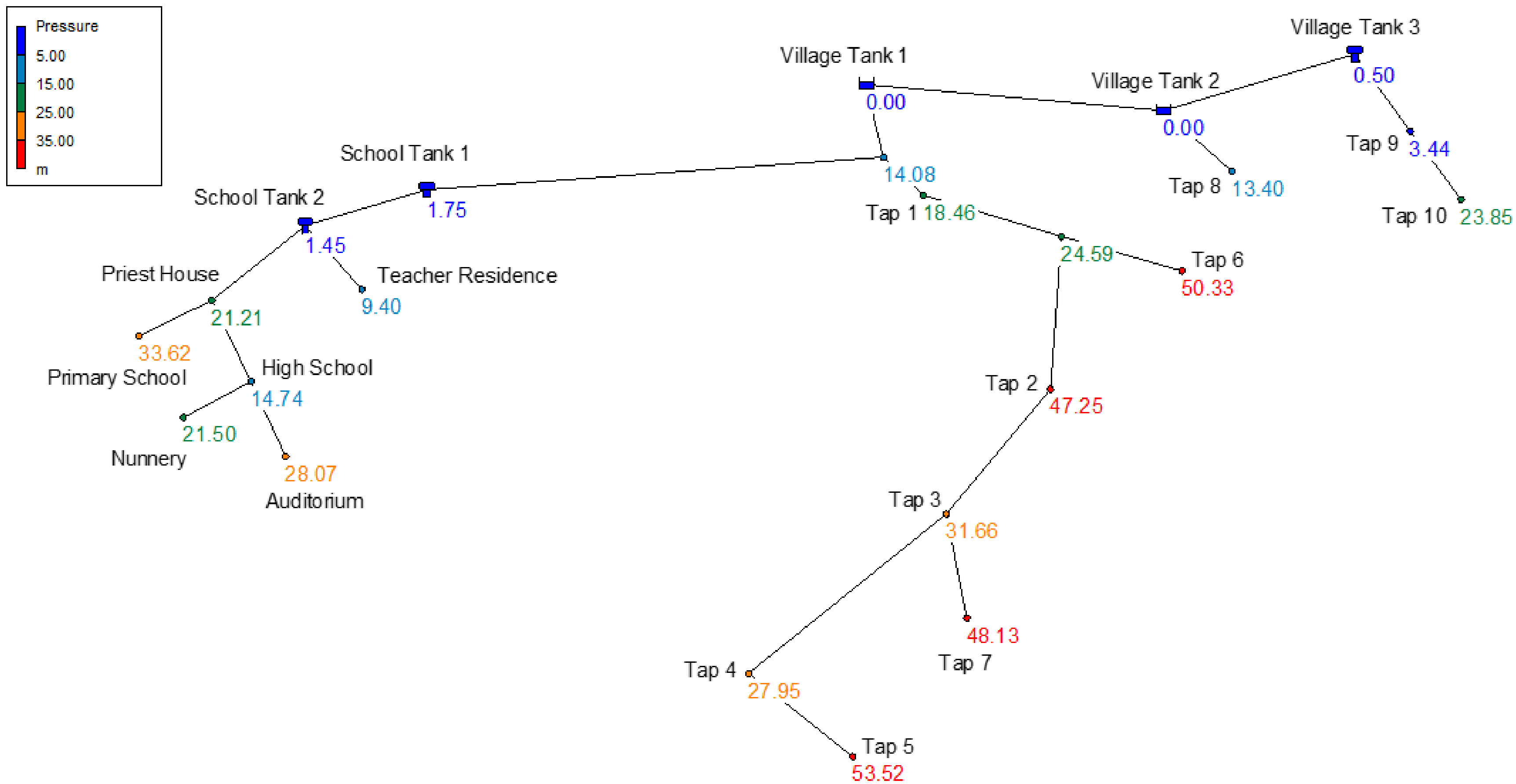


Figure 24: Scenario 2 Pipe System Pressures at 7:00 hours
(image created by author)

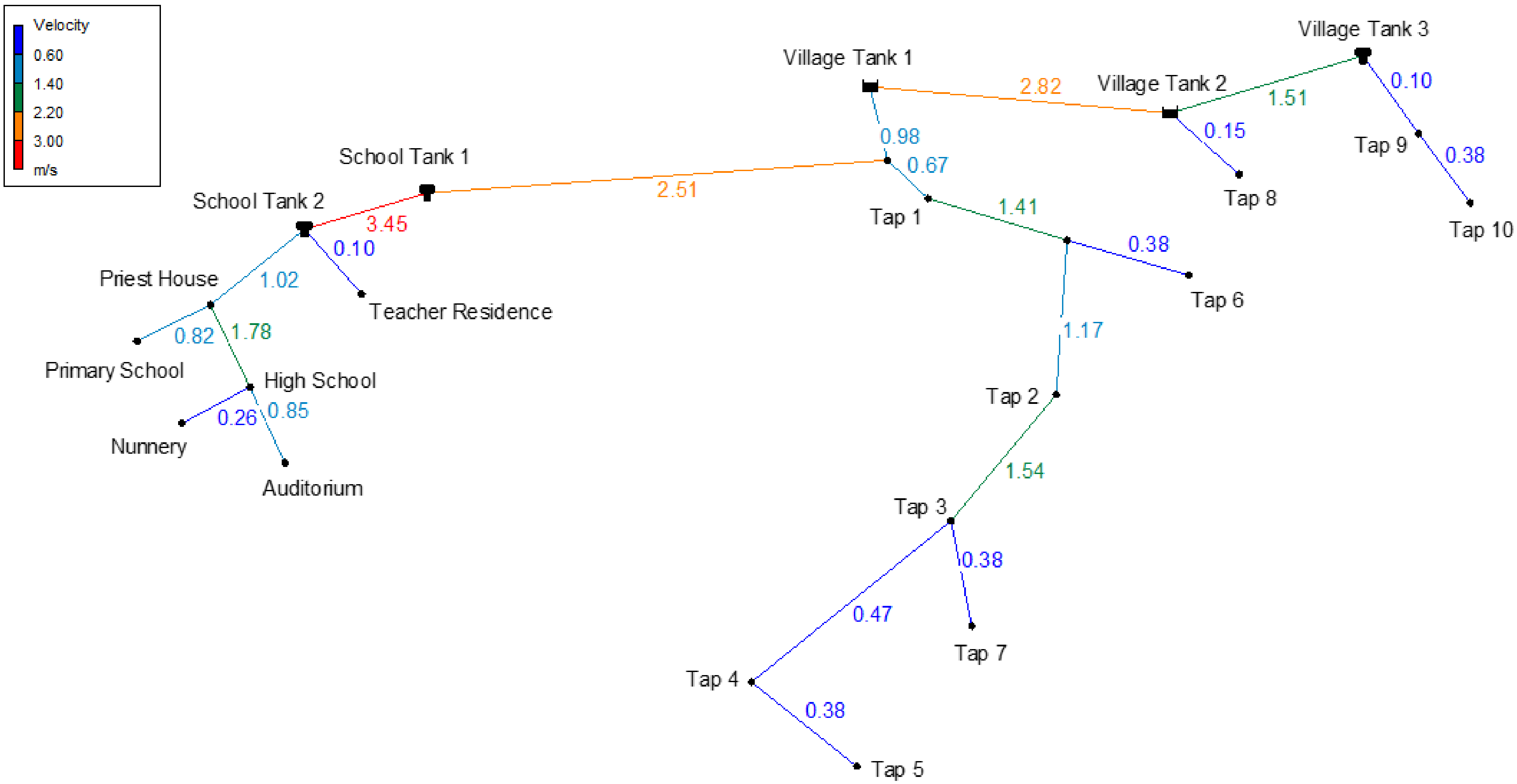


Figure 25: Scenario 2 Pipe System Velocities at 7:00 hours
(image created by author)

# 4 Conclusions

Additional research is required before implementing an updated system based off the two scenarios presented. Various demands were excluded from the calculations. For example, the school campus utilizes an underground sprinkler system to maintain the landscape. In addition, the high school curriculum includes agriculture and animal husbandry. Lastly, the high school has a chemistry lab that is occasionally used. These activities include additional water demands that were not calculated. Furthermore, other water demands could have been overlooked. It is possible these demands could be met with the scenarios presented, specifically if no event were occurring at the auditorium, however, more research is needed to confirm that theory.

Furthermore, additional upgrades could be combined with an updated system. For example, an irrigation system would highly benefit the village. Many Basotho who live in Ha Leronti heavily depend on subsistence agriculture; but, with the effects of climate change on precipitation levels and shifting seasons, it is becoming more difficult to survive on subsistence farming in the mountains. Therefore, if the reliance on timely precipitation was eliminated through an irrigation system, food security in Ha Leronti would increase. However, further inquiry is needed to determine the costs of an updated system, as well as any additional upgrades.

Nonetheless, there is still the question of where to source the additional water to meet the demands for an updated system. The existing tap system solely sources its water from two nearby mountain springs, but it can only meet the demands of both the school campus and the village during times with excessive precipitation. Therefore, to meet the peak demands of the school campus and the basic daily water amount of 30 liters per person for the village, the system will need to be augmented from other sources. Groundwater is a potential solution; however, more research is needed to determine if that would be a sustainable option. In addition, groundwater would require electricity to pump it to the tanks.

Recent developments about the existing tap system have emerged. As of January 2021, the village portion of the tap system is no longer operational. At this time, little information is available as to why it has stopped working. The assumption is that either the mountain springs could no longer accommodate both the demands of the school campus and village, and therefore, the village portion was disconnected, or the village portion of the system has fallen into disrepair. Before implementing an updated system based off the two scenarios presented, more research is required into why the village taps are no longer operational.

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# Appendix A. Written Permission from ATPS to use Figure 1

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**Sarah Peterson** <snpeters@mtu.edu>
to info

Feb 10, 2021, 12:43 PM

Hello,

My name is Sarah Peterson and I am a Master's student at Michigan Technological University. I am writing a case study on a gravity fed mountain spring tap system in Lesotho. For my case study I am trying to give my audience a well-rounded picture of Lesotho and I was hoping I could get permission to use Figure 1 from the article titled "Assessment of the impacts and adaptive capacity of the Machobane Farming System to climate change in Lesotho." I would greatly appreciate it if I could be directed to who owns the copyright of the article so that I may be able to contact them directly for permission.

Thank you in advance.
Sarah Peterson

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**nozor@atpsnet.org**
to me, info@atpsnet.org

Tue, Feb 16, 10:42 AM

Dear Sarah,

Thank you for reaching out to us for permission to use Fig.1 in our published ATPS Working Paper No. 60 titled "Assessment of the impacts and adaptive capacity of the Machobane Farming System to climate change in Lesotho".

We note that this permission is for academic purposes and therefore grant you the permission to use the said figure in the Working Paper referred.

All the best in your research work and do share with us the results of your findings.

Sincerely,
Nicholas
""""

Dr. Nicholas Ozor
Executive Director
African Technology Policy Studies Network (ATPS)*

# Appendix B. EPANET Status Report 1

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Page 1                                   Fri Mar 26 14:38:10 2021

******************************************************************
*                           E P A N E T                          *
*                   Hydraulic and Water Quality                  *
*                   Analysis for Pipe Networks                   *
*                         Version 2.00.12                        *
******************************************************************

Analysis begun Fri Mar 26 14:38:10 2021

WARNING: System unbalanced at 0:00:00 hrs.

WARNING: System unbalanced at 1:00:00 hrs.

WARNING: System unbalanced at 1:09:07 hrs.

WARNING: System unbalanced at 2:00:00 hrs.

WARNING: System unbalanced at 3:00:00 hrs.

WARNING: System unbalanced at 4:00:00 hrs.

WARNING: System unbalanced at 4:13:22 hrs.

WARNING: Negative pressures at 5:00:00 hrs.

WARNING: Negative pressures at 6:00:00 hrs.

WARNING: Negative pressures at 6:13:37 hrs.

WARNING: Negative pressures at 7:00:00 hrs.

WARNING: Negative pressures at 7:06:27 hrs.

WARNING: Negative pressures at 8:00:00 hrs.

WARNING: Negative pressures at 8:07:21 hrs.

WARNING: Negative pressures at 9:00:00 hrs.

WARNING: Negative pressures at 9:09:52 hrs.

WARNING: System unbalanced at 10:00:00 hrs.

WARNING: System unbalanced at 10:50:35 hrs.

WARNING: System unbalanced at 11:00:00 hrs.

WARNING: System unbalanced at 11:17:24 hrs.

WARNING: System unbalanced at 12:00:00 hrs.
```

```
WARNING: Negative pressures at 13:00:00 hrs.
WARNING: System unbalanced at 13:00:00 hrs.

WARNING: Negative pressures at 13:17:55 hrs.
WARNING: System unbalanced at 13:17:55 hrs.

WARNING: System unbalanced at 14:00:00 hrs.

WARNING: Negative pressures at 15:00:00 hrs.

WARNING: Negative pressures at 15:08:50 hrs.

WARNING: Negative pressures at 16:00:00 hrs.

WARNING: Negative pressures at 16:24:07 hrs.

WARNING: Negative pressures at 16:34:02 hrs.
WARNING: Node 18 disconnected at 16:34:02 hrs
WARNING: Node 20 disconnected at 16:34:02 hrs
WARNING: Node 23 disconnected at 16:34:02 hrs
WARNING: Node 19 disconnected at 16:34:02 hrs
WARNING: Node 22 disconnected at 16:34:02 hrs
WARNING: Node 21 disconnected at 16:34:02 hrs
WARNING: System disconnected because of Link 18

WARNING: Negative pressures at 16:37:19 hrs.

WARNING: Negative pressures at 16:39:37 hrs.
WARNING: Node 18 disconnected at 16:39:37 hrs
WARNING: Node 20 disconnected at 16:39:37 hrs
WARNING: Node 23 disconnected at 16:39:37 hrs
WARNING: Node 19 disconnected at 16:39:37 hrs
WARNING: Node 22 disconnected at 16:39:37 hrs
WARNING: Node 21 disconnected at 16:39:37 hrs
WARNING: System disconnected because of Link 18

WARNING: Negative pressures at 16:40:22 hrs.

WARNING: Negative pressures at 16:40:53 hrs.
WARNING: Node 18 disconnected at 16:40:53 hrs
WARNING: Node 20 disconnected at 16:40:53 hrs
WARNING: Node 23 disconnected at 16:40:53 hrs
WARNING: Node 19 disconnected at 16:40:53 hrs
WARNING: Node 22 disconnected at 16:40:53 hrs
WARNING: Node 21 disconnected at 16:40:53 hrs
WARNING: System disconnected because of Link 18

...................Warnings continue for 48 pages...................

WARNING: System unbalanced at 168:00:00 hrs.

Analysis ended Fri Mar 26 14:38:11 2021
```

# Appendix C. EPANET Status Report 2

```
Page 1                                      Sat Mar 27 22:34:25 2021

******************************************************************
*                           E P A N E T                          *
*                   Hydraulic and Water Quality                  *
*                   Analysis for Pipe Networks                   *
*                         Version 2.00.12                        *
******************************************************************

Analysis begun Sat Mar 27 22:34:25 2021

WARNING: System unbalanced at 0:00:00 hrs.

WARNING: System unbalanced at 1:00:00 hrs.

WARNING: System unbalanced at 2:41:02 hrs.

WARNING: System unbalanced at 3:00:00 hrs.

WARNING: System unbalanced at 3:02:28 hrs.

WARNING: System unbalanced at 3:44:24 hrs.

WARNING: System unbalanced at 3:51:11 hrs.

WARNING: System unbalanced at 4:00:00 hrs.

WARNING: System unbalanced at 4:24:01 hrs.

WARNING: Negative pressures at 5:00:00 hrs.

WARNING: Negative pressures at 5:04:38 hrs.

WARNING: Negative pressures at 6:00:00 hrs.

WARNING: Negative pressures at 6:25:34 hrs.

WARNING: Negative pressures at 7:00:00 hrs.

WARNING: Negative pressures at 7:24:27 hrs.

WARNING: Negative pressures at 8:00:00 hrs.

WARNING: Negative pressures at 8:14:16 hrs.

WARNING: Negative pressures at 9:00:00 hrs.

WARNING: Negative pressures at 9:16:00 hrs.

WARNING: System unbalanced at 10:47:48 hrs.

WARNING: System unbalanced at 11:03:47 hrs.
```

WARNING: System unbalanced at 14:27:38 hrs.

WARNING: Negative pressures at 15:00:00 hrs.

WARNING: Negative pressures at 15:07:07 hrs.

WARNING: Negative pressures at 16:00:00 hrs.

WARNING: Negative pressures at 16:17:56 hrs.

WARNING: Negative pressures at 17:00:00 hrs.

WARNING: Negative pressures at 17:26:46 hrs.

WARNING: Negative pressures at 18:00:00 hrs.

WARNING: Negative pressures at 18:32:11 hrs.

WARNING: Negative pressures at 19:00:00 hrs.

WARNING: Negative pressures at 19:06:51 hrs.

WARNING: System unbalanced at 20:00:00 hrs.

WARNING: System unbalanced at 20:04:41 hrs.

WARNING: System unbalanced at 20:25:43 hrs.

WARNING: System unbalanced at 21:22:31 hrs.

WARNING: System unbalanced at 23:39:39 hrs.

WARNING: Maximum trials exceeded at 24:00:00 hrs. System may be unstable.

WARNING: System unbalanced at 24:54:40 hrs.

WARNING: System unbalanced at 25:00:00 hrs.

WARNING: System unbalanced at 25:14:36 hrs.

WARNING: System unbalanced at 27:59:51 hrs.

WARNING: System unbalanced at 28:00:00 hrs.

WARNING: System unbalanced at 28:00:25 hrs.

....................Warnings continue for 8 pages....................

WARNING: System unbalanced at 166:27:53 hrs.

Analysis ended Sat Mar 27 22:34:27 2021