Majuro Water Supply and Distribution System Analysis

Majuro Atoll
The Republic of Marshall Islands

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

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Office of Insular Affairs
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Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Cover Photo: Majuro Atoll (Reclamation, 2020)

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Prepared by the Technical Service Center, Bureau of Reclamation for the Office of Insular Affairs and the Majuro Water and Sewer Company

Prepared by:

MIKE LIN Digitally signed by MIKE LIN
Date: 2020.09.17 09:20:27 -06'00'

Mike Lin, Ph.D., PE, Civil Engineer, Water Conveyance Group

PATRICK WRIGHT Digitally signed by PATRICK WRIGHT
Date: 2020.09.17 09:40:51 -06'00'

Patrick Wright, Physical Scientist, Geographic Applications & Analysis Group

MICHELLE NORRIS Digitally signed by MICHELLE NORRIS
Date: 2020.09.17 09:15:10 -06'00'

Michelle Norris, PE, Civil Engineer, Water Conveyance Group

Peer reviewed by:

WYLIE DUKE Digitally signed by WYLIE DUKE
Date: 2020.09.17 09:12:06 -06'00'

Chris Duke, PE, Manager, Water Conveyance Group

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Acronyms and Abbreviations

AWWA	American Water Works Association
CIPP	cured-in-place pipe
DOI	U.S. Department of the Interior
DUD	Delap-Uliga-Darrit
FCV	flow control valve
EPA	U.S. Environmental Protection Agency
EPS	Extended Period Simulations
GIS	Geographical Information System
gpcd	gallons per capita per day
gpm	gallons per minute
HGL	hydraulic grade line
HP	horsepower
JICA	Japan International Cooperation Agency
MG	million gallons
MWSC	Majuro Water and Sewer Company
NRW	nonrevenue water
PVC	polyvinyl chloride
PRV	pressure reducing valve
PSI	pounds per square inch
PSV	pressure sustaining valve
Reclamation	Bureau of Reclamation
Rita	Darrit
RMI	Republic of Marshall Islands
RO	reverse osmosis
RW	raw water
SWM	solid waste management
TSC	Technical Service Center (DOI, Reclamation)
TW	treated water
USACE	United States Army Corps of Engineers
WHO	World Health Organization
WTP	water treatment plant

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Executive Summary

Background and Need

The Republic of Marshall Islands' (RMI) main population center is on the Majuro Atoll, one of the 29 coral atolls north of the equator in the central Pacific Ocean. About 28,000 people live on the atoll (RMI 2012). About 80% of the population rely on private tanks that collect rainwater for water, and only about 20% of the households have service connections to the integrated system of water treatment plants that treat water from wells and rainwater collection (Johnston 2013). The system pumps water to private tanks for about four hours a day usually three times a week to help fill these residential and institutional tanks. Moreover, as water in the system is mixed together with water collected from household and institution roofs, the water quality in their tanks does not meet the standards for potable water, and most people buy drinking water or treat the water at home with disinfectants.

The Majuro Water and Sewer Company (MWSC) requested aid from the U.S. Department of the Interior's DOI's Office of Insular Affairs to identify and evaluate potential system improvements, including system monitoring and determining sources/locations of non-revenue water. The Office of Insular Affairs' goal is to increase support of the Freely Associated States, as well as to support United States' foreign policy objectives.

About this Study

To help provide a basis for decision making for improving the water systems on the Majuro Atoll, Reclamation's Technical Service Center (TSC) conducted an engineering assessment of the existing system, gathered data and information, and developed a hydraulic computer model and geographical information system (GIS) database. This study:

- provided an inventory of the existing water network systems (Section 2),
- developed a hydraulic model to facilitate the design and analysis of present and future network systems (Section 3),
- evaluated the adequacy of the existing distribution systems and identified deficiencies (Section 4),
- provided conceptual details of potential improvements to satisfy the system's present and future needs (Section 5), and
- recommended system improvements and next steps (Section 6)

This final summary engineering report details the model development and use as well as system improvement suggestions for MWSC to consider. Appendices A – D provide data for the model scenarios.

Existing Majuro Municipal Water Supply, Storage, and Distribution System

The existing system consists of rainwater collection from the airport runways, individual rooftop collection systems (public and private). Groundwater is also collected through wells located in Laura, Delap and a single saltwater well is treated through a reverse osmosis system and provided directly to the hospital surgical ward. GIS and hydraulic models were developed to incorporate these water sources as well as the existing infrastructure of asbestos-cement and PVC pipe transmission and service mains. Reservoirs, tanks, wells and pump stations were modeled to reflect current operation scenarios. The model was first developed to confirm the system existing conditions, then proposed improvements were modeled and tested to determine their effectiveness.

The system consists of three subsystems as shown in Figure ES-1:

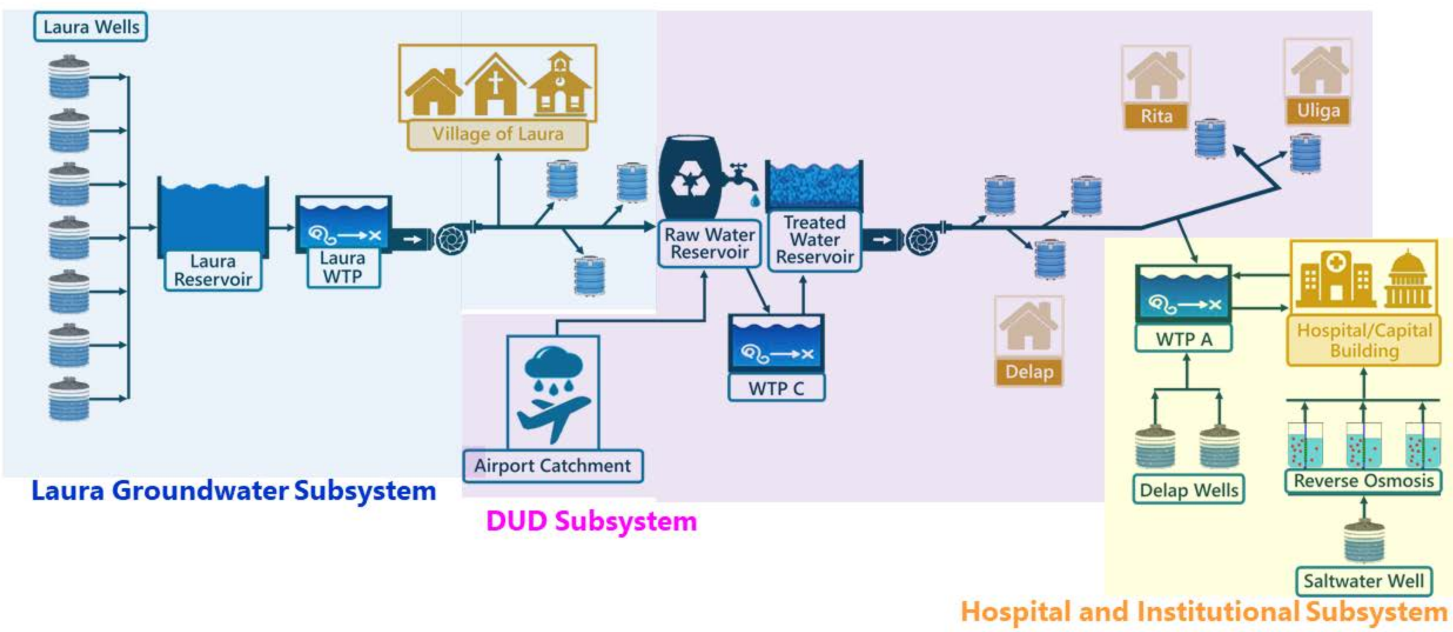

Figure ES-1. Existing Majuro municipal water supply storage and distribution system. DUD is Delap-Uliga-Darrit Darrit is referred to as Rita.

Existing System Deficiencies

Existing deficiencies include:

- Many households do not have rainwater storage tanks, or rainwater collection is low due to missing gutters or improper piping arrangement.

- There is not enough water supply during the dry season.

- The percentage of nonrevenue water is high due to either pipe leakage and/or illegal connections.

- As the demand is greater than the supply, the system can only operate on an intermittent basis.

- There is a high rate of system pressure drop over the long stretch of service areas from the airport to Rita. The Rita area at the end of the DUD system frequently gets little to no pressure. With no pressure, there is no water delivery.

- Only a small percentage of the atoll's population is connected to the system.

- Where existing asbestos-cement pipe is cracked or has faulty joints, water leaks from the pipe while it is pressurized. When the pipe is not pressurized or experiences negative pressure as a result of emptying the pipeline, groundwater adjacent to the pipeline may enter the pipe – introducing salt water and contaminants to the water supply, which is out of compliance with U.S. Environmental Protection Agency (EPA) and the American Water Works Association (AWWA) recommendations.

System Improvements

Proposed system improvements are based on the model as well as findings of the January 2020 site visit, including discussions with the MWSC. Improvement Scenario modeled actions were:

- Install rainwater household storage tanks
- Replace ductile iron pipe sections at bridge
- Repair all asbestos-cement pipes with cured in place pipe
- Install a new standpipe
- Install flow control valves
- Provide a combination air valve at bridge
- Install a pressure sustaining valve in the Laura pipeline at the exit to the reservoir at the airport

Other phased improvements were suggested but not modeled:

- Install public standpipes
- Develop a rainwater reservoir at Bokiur Island
- Improve the hospital reverse osmosis (RO) system
- Provide an elevated tank for the Laura subsystem

Conclusions and Recommendations

RMI is planning capital improvements to the system in phases as priorities and funding availability allow.

While a water system that provides treated water 24 hours a day may not be possible, the improvements noted in Section 5. *System Improvements* would significantly increase the level of service to people who are currently unserved or underserved. Improvements are ranked for cost, benefit, and urgency (see Section 6.2). Most of these actions can be installed independently of other solutions, and there is no particular order. Note that installing the new 400,000-gallon standpipe would depend on installing flow control valves first. Some improvements will have large impacts on system operation with relatively minimal capital expenditures. In general, the improvements that will provide the most benefit include:

- Installing flow control valves provides the best cost benefit as it is relatively inexpensive, benefits all users, and would allow the system to operate more uniformly and efficiently.

- The combination air valve at the bridge would remove trapped air at the high point of the system, allowing water flow.

- The system downstream of the ductile iron pipes at the bridge depends entirely on the reliability of these pipes, so repairs before these pipes break is imperative.

- Although repairing pipe with cured-in-place pipe (CIPP), is expensive and therefore ranked low as an alternative, the benefit is very high—as this will prevent breaks, eliminate joint leaks, and improve water quality.

1. Introduction

1.1. Study Purposes and Scope

To help provide a basis for decision making for improving the water systems on the Majuro Atoll, Reclamation's TSC's Water Conveyance design staff in Denver, Colorado conducted an engineering assessment of the existing system, gathered data and information, and developed a hydraulic computer model and GIS database. Simulations of the base model can be used to identify deficiencies and proposed modifications to the existing system. This final summary engineering report details the model development and use as well as system improvement suggestions for MWSC to consider.

This study:

- provided an inventory of the existing water network systems (Section 2),
- developed a hydraulic model to facilitate the design and analysis of present and future network systems (Section 3),
- evaluated the adequacy of the existing distribution systems and identified deficiencies (Section 4),
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The project is focused on the freshwater system of the Majuro Atoll. The team recognizes there is a significant issue related to the mixing of MWSC provided water and the water from roof collection systems. At this time, a priority on potability was not high due to this issue. It was felt that addressing reliability and sufficient supply was more pressing as a first priority. The sanitary system of the Majuro Atoll is not evaluated in this scope of work.

Through the site visit and discussions with MWSC, the team gained an understanding of the culture and societal practices impacting MWSC operations. These items must be recognized in the development of the hydraulic and GIS models in such a way that they will be useful to the MWSC. It is also critical to recognize their ability to implement recommendations and ensure engineering assistance is provided during the implementation process.

These items have been recognized in developing the hydraulic and GIS models in such a way to attempt to provide a useful guide to the MWSC. Recommendations have been provided in a manner to provide projects that can be implemented individually recognizing the ability to implement various recommendations will vary due to financial and schedule constraints. See Section 6.2 *Conceptual Decision Matrix for Recommended System Improvements.*

1.2. Study Area

1.2.1. Location

The project is in the Majuro Atoll, one of the RMI's 29 coral atolls just north of the equator (Figure 1). RMI shares maritime boundaries with the US Midway to the north, Kiribati to the southeast, and Federated States of Micronesia to the west. Majuro is the capital of the Republic of Marshall Islands.

The atoll has a total land area of about 3.7 square miles. This narrow band of land extends about 20 miles from the Village of Laura in the west to Delap-Uliga-Darrit (DUD) in the east. The Village of Laura has the highest elevation point on the atoll, estimated at less than 3 meters (10 feet) above sea level (Palaseanu-Lovejoy 2017).

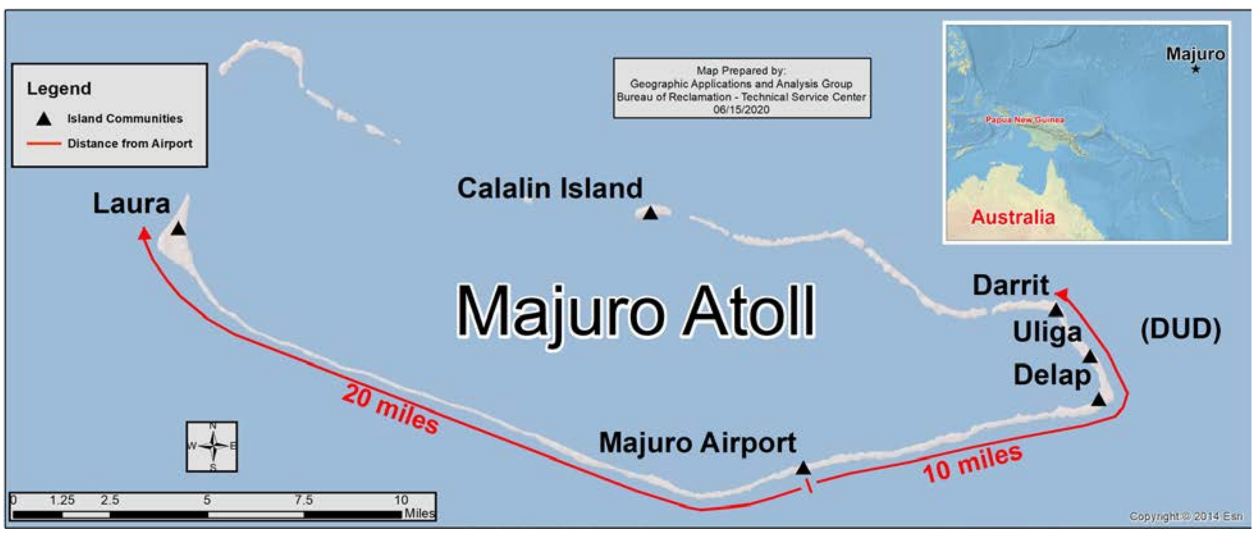

Figure 1: Majuro Atoll in the Republic of Marshall Islands (RMI). Darrit is also known as Rita (Reclamation, 2020).

1.2.2. Water Supply and Demand

As the RMI's capital, Majuro Atoll is the country's political and economic center. Gale and deBrum (2017) describe this as a highly urbanized area, with about 28,000 people. About 24,000 live in the area from the airport to Darrit (Rita).

As described by the Asian Development Bank, (2020) “The provision of urban services in Majuro, including water supply, sanitation, and [solid waste management] SWM, is insufficient. Only 25% of households have access to intermittent public water supply, and its quality is compromised. The aged water supply system is damaged and the level of nonrevenue water (NRW) in 2018 was estimated at 70%, of which two-thirds is estimated to be due to leakage from the main and service connection pipelines. Most households capture rainfall but rely on the public water supply system to replenish rainwater tanks, particularly during dry periods.” These dry periods are usually from January to March but have extended through April in the most severe droughts (Gale and deBrum 2017).

About half of the residents do not rely on the MWSC water supply. Gale and deBrum also cite a 2016 MWSC community survey that found that “52% of residents use their own or neighbor’s rainwater catchment for drinking water and 39% purchase bottle water for drinking water. There are at least eight commercial drinking water suppliers providing bottled drinking water.” While this household rainwater harvesting is a major component of Majuro’s water system, it depends on high levels of rainfall, and individual systems are reported to be in poor condition and tanks may be too small to provide adequate storage. Moreover, these unconnected tanks can be emptied in two to four weeks during the low rainfall periods (Gale and DeBrum 2017). The MWSC water supply runs only about four hours at a time three times a week, from 4:30 p.m. to 8:30 p.m. to replenish household and larger institutional water tanks.

1.2.3. Challenges

Majuro Atoll is a complex water system, addressing many challenges, including:

- **Floods.** As Palaseanu-Lovejoy (2017) describe the area: “The low-lying Majuro Atoll is extremely vulnerable to sea-level rise, tsunamis, storm surge, coastal flooding, and climate change that could impact the sustainability of the infrastructure, groundwater, and ecosystems.”

- **Droughts.** As the atoll depends on rainwater, droughts can quickly cause severe water shortages (for example, Andrews 2016) and affect groundwater quantity and quality (for example, Presley 2005).

- **Water-borne illnesses.** Illnesses from poor water quality have increasing costs. For example, RMI’s Economic Policy Office (2010) estimated “that between 2001 and 2006 the estimated costs of treatment for gastroenteritis alone, increased by 87%, for an annual estimated cost of nearly $445,000.”

- **Financial.** Economic Policy (2010) reports that “according to the survey results, 46.6% of all households on Majuro and Kwajalein earned less than $10,000 annually” and noted that “the lower the income level is, the more likely that the household will be without household water storage.”

2. Existing Water System Inventory

2.1. Private Systems

In the thousands of private systems, some homes and institutions are equipped with rainwater catchments on rooftops and private storage tanks. Only about a third of the homes also receive water from the municipal system. Economic Policy (2010) noted that about 32% of the population did not have water catchments. Out of the total of the 3,620 households that responded to the survey, 1,609 reported that water was not available from their main source throughout the year.

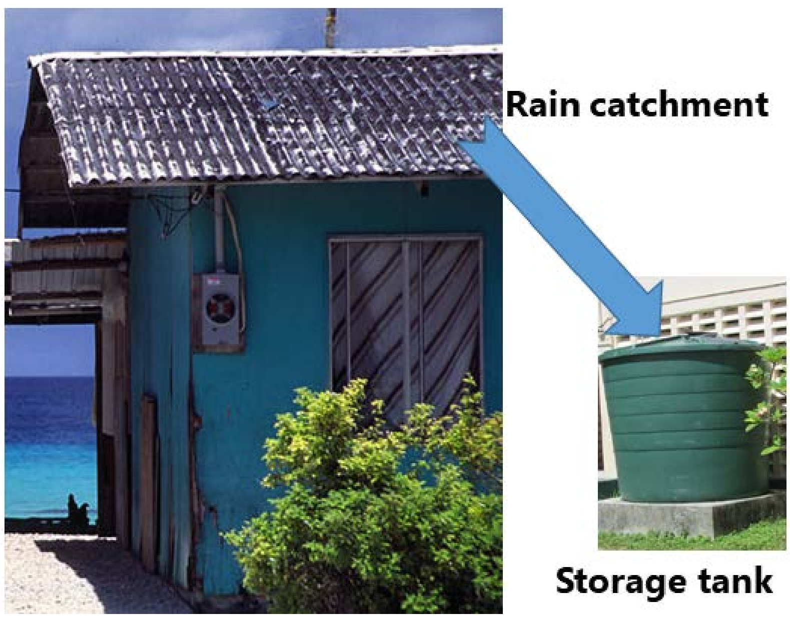

Figure 2: Private rainwater catchment and storage system (house photo is courtesy of Stefan Lins, used under creative commons, and tank photo is from Reclamation 2020).

Water quality is a concern for households using these tanks, because the tanks receive rainwater collection from the household roof, as well as treated water from WTP C. These two sources of water are mixed. As a result, it is impossible to safeguard the quality of water in the tanks. Clorox and other household bleach products are commonly used for disinfecting tank water before consumption.

2.2. Municipal System

Majuro primarily uses rainwater to support their potable water needs. Groundwater and saltwater supplement their supplies.

The Majuro municipal water supply, storage, and distribution system consists of three subsystems (Figure 3):

- **Laura Groundwater Subsystem:** Seven wells provide water for the western end of the atoll and the Village of Laura. This water is stored in the Laura Reservoir, treated at the Laura water treatment plant (WTP), and pumped through the system, connecting to the other systems to supplement as needed.

- **Delap-Uliga-Darrit (DUD) Subsystem**: 74 acres of rainwater catchment at the airport runway discharge rainwater to raw water reservoirs, which is treated at WTP C, stored in treated water reservoirs, and pumped to the Darrit (Rita) end of the island.

- **Hospital and Institutional Subsystem:** Rooftop catchments from the hospital and capital building complex and Delap wells provide raw water to WTP A, which serves the hospital and other buildings. Three RO units provide treated water exclusively for the surgical ward.

WTP B is no longer in operation and was not included in this study.

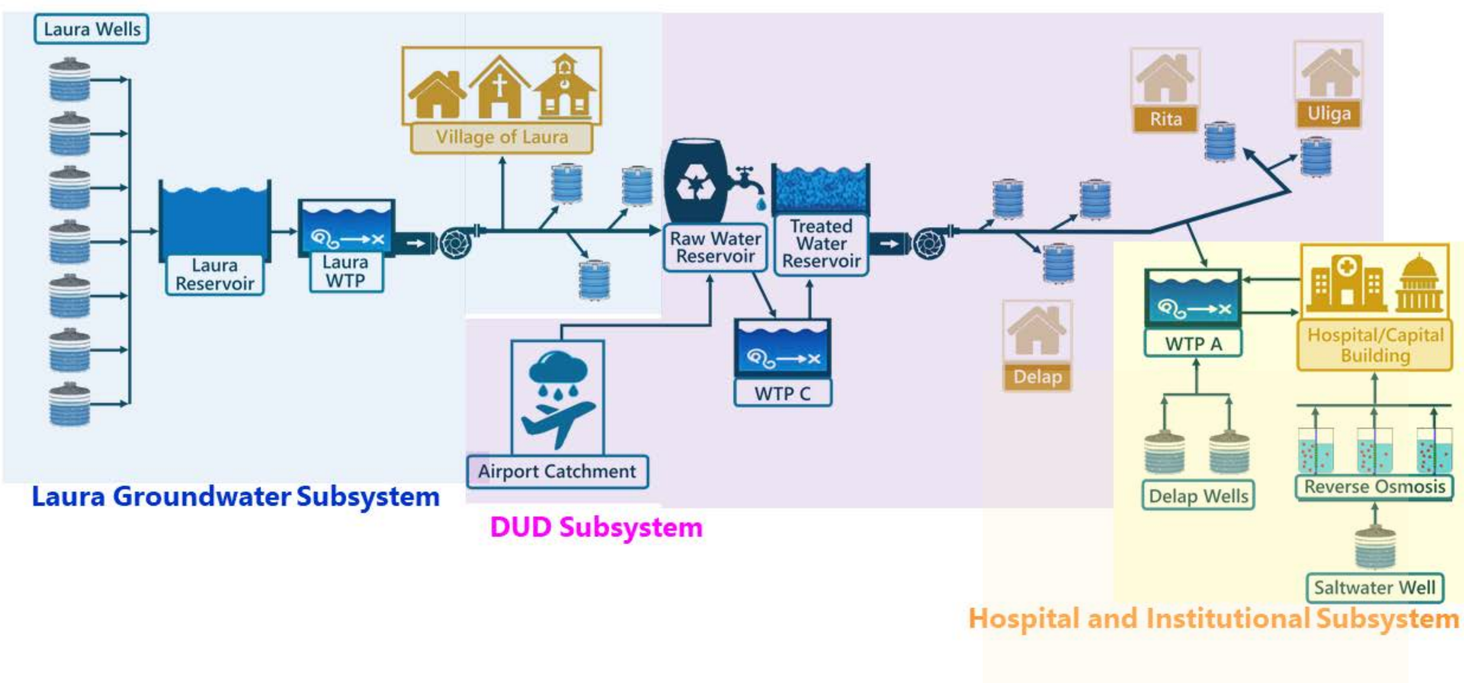

Figure 3: Schematic of Majuro's existing water supply system (Reclamation, 2020).

2.2.1. Laura Groundwater Subsystem

Seven dedicated Ranney Wells supply water to the Laura Reservoir (Figure 4), which feeds the Laura WTP.

After treatment, water is lifted through the Laura Pump Station (Figure 5), which houses two 15-horsepower (HP) pumps rated at 300 gpm and 125 feet of head; and one 5-HP pump rated at 115 gpm and 145 feet of head. The two 15-HP pumps supplement water to the DUD system served by WTP C.

The single 5-HP pump supplies water to the Village of Laura and several small residences along the 20 miles of transmission pipe from Laura WTP to the International Airport.

Figure 4: Laura Reservoir for untreated water prior to treatment at Laura WTP (Reclamation photo 2020).

Figure 5: Laura Pump Station with three pumps (Reclamation photo 2020).

2.2.2. DUD Subsystem

Rainwater harvesting from the 74 acres of rainwater catchment at the Majuro International Airport runway is the primary source of potable water for Majuro. This raw, untreated rainwater is currently stored in five reservoirs. A new raw water reservoir is currently being planned in cooperation with the Japan International Cooperation Agency. Figure 6 shows the volumes and location of these reservoirs.

Water from these raw water reservoirs is treated at WTP C with two automatic valveless gravity sand filters (Figure 7). Each unit has a capacity of 500 gallons per minute (gpm).

Treated water from WTP C is then stored in two treated water reservoirs (Figure 8).

From WTP C, treated water is pumped through Majuro's parallel transmission system to serve the DUD service area. From the WTP C, three pumping units, rated for 800 gpm each, lift water to the DUD service area (Figure 9).

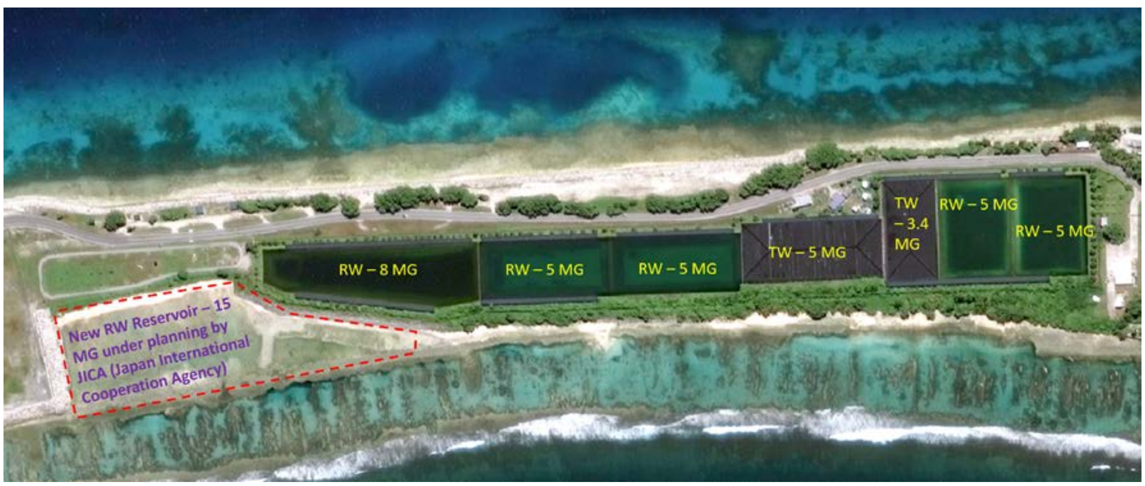

Figure 6: Reservoirs near the airport. RW = raw water, TW = treated water, and MG = million gallons.[1]

In summary, the existing reservoirs store 28 MG of raw water and 8.4 MG of treated water. The Japan International Cooperation Agency (JICA) is planning one new 15 MG raw water storage reservoir.

[1] Note that all aerial photography used in the model and this report comes from Esri, Maxar, GeoEye, Earthstar Geographics, National Centre for Space Studies/AirbusDS, United States Department of Agriculture, United States Geological Survey, AeroGRID, IGN, and the GIS User Community.

Figure 7: Two automatic valveless gravity filters at WTP C (Reclamation, 2020).

Figure 8: Treated water reservoir at the Majuro International Airport (Reclamation, 2020).

Figure 9: Three pumping units at WTP C. Each pump is rated for 162 feet of head and 800 gpm (Reclamation, 2020).

2.2.3. Hospital and Institutional Subsystem

There are three sources of water for the hospital and capital building:

- groundwater from two Delap Wells,
- rainwater collected from the rooftops of the hospital, capital building complex, and other institutional buildings, and
- pumped water from a saltwater well.

Water Treatment Plant A treats the groundwater and rooftop rainwater.

Figure 10 shows a temporary holding pond for raw water from the Delap Wells and rooftop rainwater. The raw water is treated at WTP A for general use in the hospital and other institutional buildings. WTP A does not supply water to the DUD service area and generally operates independently of WTP C. However, any excess water in the DUD subsystem goes to the WTP A as part of the supply for the hospital and institutional subsystem.

One dedicated deep well pumps groundwater intruded from the sea into three RO units to generate high quality water exclusively for the hospital's surgical ward. (Figure 11). The concentrate is discharged back to the sea. The RO treated water is stored on site in dedicated storage tanks (Figure 12).

Figure 10: Raw water temporary holding pond at WTP A (Reclamation, 2020).

Figure 11: RO units for hospital water (Reclamation, 2020).

Figure 12: Storage tanks for water treated with RO (Reclamation, 2020).

2.3. Development History

The existing DUD rain catchment systems, WTP C, WTP A, and water distribution system were developed by the United States Army Corps of Engineers (USACE) in the 1970s. The system was subsequently improved in the late 1990s through the early 2000s with loans from the Asia Development Bank (Asian Development Bank 1995, Asia Development Bank Office of Pacific Operations 1999, Fraser Thomas Partners 2001, and Asian Development Bank 2004). However, the three RO units were not implemented until 2017 with a grant from JICA. The Village of Laura's system was implemented in the 1980s by the Majuro Department of Public Works.

3. Hydraulic Model

3.1. Objectives

The objectives of the hydraulic network modeling of the water distribution systems are to:

- provide an inventory of the existing water network systems,
- evaluate the adequacy of the existing distribution systems,
- identify deficiencies in present systems—if any,
- develop improvement programs to satisfy the system's present and future needs, and
- develop a computer model to facilitate the design and analysis of present and future network systems.

3.2. Background Information

A comprehensive literature research was carried out in the collection of data and information related to the existing water supply and distribution system. Documents collected include system GIS database, reports of census data, household water survey, and previous system improvements (Asian Development Bank 1995, Asia Development Bank Office of Pacific Operations 1999, Fraser Thomas Partners 2001, RMI 2010, RMI 2012, and Johnston 2013). In addition, a physical site visit was attended by three TSC staff in January 2020. The existing data, reports, and site visit were critical to TSC's understanding of the project needs and desired outcomes.

3.3. GIS Database

TSC consolidated GIS data to provide a single GIS database, including approximate alignments of existing main transmission and service connection pipelines, was the basis of the alignments used to develop the model.

3.4. Model Components

A network model composed of the GIS database and a computer program manipulates the network data (including physical and operational data) and performs the necessary calculations (Figure 13).

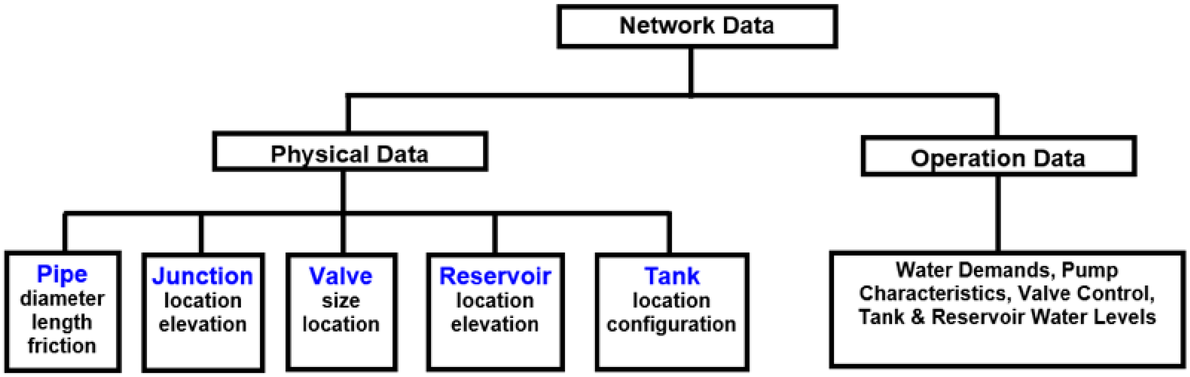

Figure 13: Schematic of hydraulic model components.

Physical data describes the network configuration and infrastructure geometry (e.g., pipe diameter, length and friction factor, valve size and location, reservoir location and elevation, and tank location). Physical elements in the model are:

- **Pipes.** Pipes are model elements that have a constant diameter, material and are connected to a junction node. Each pipe is assigned a friction factor C-value, depending on the age, material, and diameter of the pipe. Location, length, and elevation are also modeled.

- **Junction nodes.** Junction nodes connect two or more pipe segments and are a point at which water demand can be assigned.

- **Valves.** Many types of valves can be incorporated into the hydraulic model, including pressure reducing valves (PRV), flow control valves (FCV), pressure sustaining valves (PSV), isolation valves, etc.

- **Reservoirs.** A reservoir represents a source of water that is not readily depleted and offers a constant source of water supply.

- **Tanks.** A tank has a limited source of water supply.

- **Pumps.** Pumps are primarily modeled as operational data. Physical components include location, elevation, and outlet diameter.

Operational data represents the actual values of system facilities (e.g., pump characteristics, valve control settings, and tank and reservoir water levels).

3.5. Computer Program

3.5.1. Modeling Capabilities

The analyses of the water distribution systems in the study area were conducted by developing and using a mathematical computer model, Bentley WaterGEMS CONNECT Edition (Bentley 2020).

When full calibration is available, WaterGEMS has the following main modeling capabilities. When data may be limited, the use of engineering judgment is utilized with the program to approximate and determine the following information with relative accuracy:

- Track and analyze the:
  - flow of water in each pipe,
  - pressure at each junction node,
  - level of the water in each tank, and
  - water quality and the age of water throughout the network system.
- Perform system operations based on both tank level and time.
- Compute pumping and energy cost.
- Find locations of leakage.

3.5.2. Modeling Scenarios

Two scenarios were modeled:

- **Existing Conditions Scenario** (called Base Scenario in the model) is based on the existing physical and operational data. Note that the 400,000-gallon standpipe near the Marshall Island High School campus was abandoned because the system pressures were insufficient to fill the tank. The standpipe was not incorporated into the Existing Conditions Scenario. Assumptions included:
  - All valves are open
  - Two pumps in operation at WTP C Pump Station
  - No flow control valves in the existing system
  - Standpipe near the high school is not in operation
  - 800 connections
- **Improved Conditions Scenario** incorporates the improvements described in Section 5.1., which include tanks, pipe repair, valves, and a new 400,000-gallon standpipe. Assumptions included:
  - Pipes do not leak (i.e., repair faulty joints, broken pipes, and address non-revenue connections).

- o All end users in the DUD and Laura service areas would be connected to the system and rely on the system for treated and piped water (i.e., either through a public standpipe or supply to the household tanks). The simplified polygon method applies the assumed demand to a polygon service area and does not differentiate between serving tanks or public standpipes.

3.5.3. Model Verification

The model development involved verifying the GIS database to reasonably represent the actual water distribution system by correlating the computed system performance against the field observed conditions.

There is difficulty in collecting reliable operation data, therefore the model is not considered to be calibrated at this stage. Hydraulic models are considered calibrated when field measurements are taken to confirm model predictions (e.g., meters to confirm flows, pressure at certain locations, tank water height over time). Hydraulic model calibration is usually an iterative process—taking recorded field measurements, plugging them into the model, then repeating the simulation until the field measurements are nearly identical to the hydraulic model predictions. In this case, resources are not currently available on site to calibrate the model by taking field measurements. Instead, TSC's model has been "verified" as a general discussion of TSC's hydraulic model findings with the team at MWSC confirmed that our findings (e.g., the system's inability to keep the standpipe pressurized is mirrored in reality). Despite the difficulty in collecting operation data, the overall verification of the model was considered acceptable. This verified model becomes the base model from which other demand conditions can be developed and compared for system analysis.

3.6. Existing Data

The data available for existing designs were used as the base for the model configuration. As-built drawings were incorporated into the GIS database, and therefore into the model as well. Major trunk mains used in transporting water from the WTP and storage facilities were identified.

To develop a model that reasonably simulates the hydraulics of the key pipelines delivering water throughout the distribution system and help reduce the complexity of the model, smaller water mains within the distribution system that either serve as major water distribution loops or are significant in representing what is typical of the distribution network were also identified. In general, water mains less than 4 inches in diameter were not identified unless they were of hydraulic significance. These pipe segments formed the basis of the base water distribution models.

Locations or junctions along the pipeline where the pipe sizes change or where two or more pipes intersect are represented by nodes. The nodes establish continuity between the pipes intersecting at these junctions. The physical data for the pipes and nodes from GIS were incorporated into the WaterGEMS model. The operating data for each system generally included pump curve data to represent the pump station flow rates and discharge pressures.

3.6.1. Transmission and Distribution Mains

The existing DUD transmission and distribution mains primarily consist of asbestos-cement and PVC pipe materials, as summarized in Table 1. Total length of pipe is approximately 22.7 miles.

Table 1: Summary of DUD Transmission and Distribution Pipe Types and Lengths.

Asbestos-cement		**PVC**	
Diameter (inches)	**Length (feet)**	**Diameter (inches)**	**Length (feet)**
-	-	4	3,744
6	9,605	6	13,406
8	4,138	8	4,136
10	7,725	10	7,792
12	34,482	12	34,923
Total Length (feet):	**55,950**	**Total Length (feet):**	**64,000**

PVC = polyvinyl chloride

The existing Laura transmission main consists of 12-inch PVC pipe, with a total length of 99,000 feet (about 18.5 miles).

3.6.2. Pumping Facilities

The farther and faster the water needs to go through a pipe, the more energy is needed to provide pressure so the flow in the pipe can travel long distances and overcome friction. Pressure comes from either gravity (flowing downhill) or pumps. As there is not enough elevation on the atoll to flow by gravity, the existing system must rely on pumps. The MWSC systems are pressurized by pump stations at Laura, WTP C, and WTP A. These pumps supply transmission pipelines, commonly known as water mains, with the energy (i.e., pressure, velocity, and elevation) needed to reach and fill smaller service connection pipelines. These small service connection pipelines then feed private storage tanks throughout the systems.

3.6.2.1. Laura Water Treatment Plant (Village of Laura System)

The Village of Laura's water system is independent of the DUD system. While not the focus of this study, water delivery from the Laura Water Treatment Plant to the airport is included in the model. A complete pump curve is not available for the Laura Pump Station. However, pumps have been identified as the American Marsh pumps with the pump characteristics listed in Table 2. For the Laura subsystem, a single point design point at the rated conditions is used for the pump performance curve in WaterGEMS simulations.

Table 2: Characteristics of Laura Pumps

Service Area	Horsepower (HP)	Number of Units	Rated Head (feet)	Rated Flow (gpm)
Village of Laura	5	1	145	115
Area from pump station to airport	15	2	125	300

3.6.2.2. Water Treatment Plant C (DUD System)

Available data for the WTP C pump curves is summarized below. The pumps have been in operation for about 20 years and are still performing as expected. Three units are installed in the pump station; one is a standby. The pump curves have been incorporated into the hydraulic model, including the standby pump for Extended Period Simulations (EPS).

Table 3 lists the pump curve provided by the pump manufacturer. The pumps are rated at 800 gpm with a head at 162 feet. Figure 14 depicts the DUD pump curve.

Table 3: DUD Pump Curve (Head and Flow) from Pump Manufacturer

Head (feet)	Flow (GPM)
210.22	0.0
201.29	200.0
188.78	400.0
183.42	500.0
175.57	600.0
168.09	700.0
162.0	800.0
147.72	900.0
122.71	1000.0

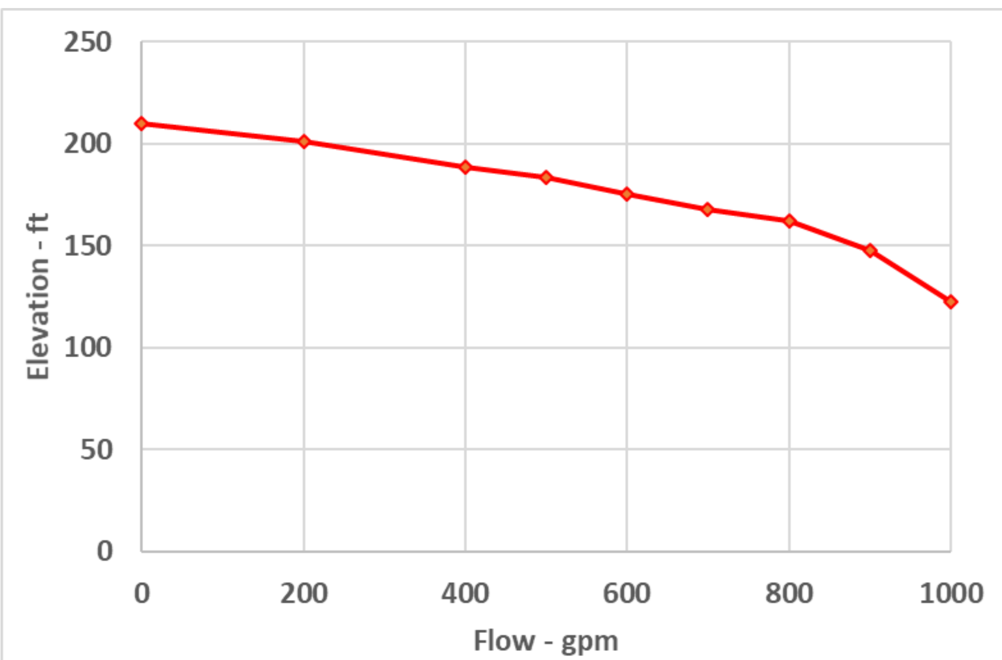

Figure 14: DUD pump curve from pump manufacturer.

3.6.2.3. Water Treatment Plant A (Hospital and Institutional System)

The system downstream of WTP A is not modeled, though the demands of WTP A service area are incorporated in the future improvements model, discussed further in Section 6. *System Improvements*.

3.6.3. Standpipe Near Marshall Island High School

The abandoned 400,000-gallon standpipe close to the Marshall Island High School campus (Figure 15) is included in the model. No as-built drawings for the standpipe were available. Based on world imagery and on-site observation, it was estimated the standpipe is approximately 35 feet in diameter and 55 feet high.

Figure 15: Abandoned 400,000-gallon standpipe (Reclamation, 2020).

The standpipe has been abandoned because the system pressures were insufficient to fill the tank, and suggestions to replace this with a new standpipe are included in Section 6. *System Improvements.* The existing standpipe cannot be used due to its current lack of structural integrity and is not in any condition to be refitted or repaired. The standpipe is not incorporated into the Existing Conditions Scenario, and its replacement is included in the Improved Conditions Scenario.

3.6.4. Household Storage Tanks

Thousands of household storage tanks are in the DUD and Laura service areas. These tanks are typically approximately 6 feet high and hold about 1,200 gallons of water.

Due to the variability in how household water is treated locally, water quality is not modeled.

3.6.5. Simplified Polygon Method to Incorporate Multiple Tank Capacities

In the DUD system, there are 77 service areas with thousands of household water storage tanks. Figure 16 illustrates the complexity of tank connections in a typical service area—showing the large transmission main, and several small distribution pipelines feeding dozens of residential storage tanks. Rather than modeling the thousand of storage tanks and myriad of distribution pipelines, each service area was simplified and represented with a single tank and a single distribution pipeline (Figure 17).

Figure 16: Sample of a single service area with multiple tanks and distribution pipelines served by the transmission main. Red lines indicate real tanks.

Figure 17: The same typical service area shown with one representative tank and distribution pipeline that is hydraulically equivalent. Pink lines indicate the boundary of modeled tanks and polygons.

Some key concepts were considered in using one tank per service area, without sacrificing the integrity of the model (Figure 18). First, all water storage capacity within the demand polygon was combined within a single tank with a larger diameter while keeping the height and base elevations about the same as all of the single small tanks within the service area. Then “D” as the diameter of the representative service connection pipeline was selected so that the headloss to all of the individual tanks in the service area was about the same as the headloss of the representative larger service connection pipeline.

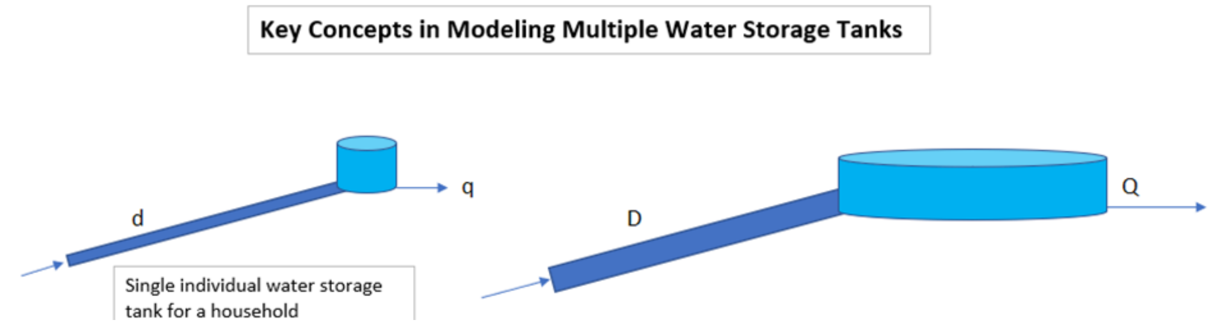

Figure 18: Summary of tank simplification approach where “q” is flow to each private storage tank identified in the existing system, and “Q” is the representative flow for the service area, “d” is the existing distribution pipeline, and “D” is the representative single distribution pipeline.

Due to the even, flat terrain on Majuro, it was assumed that the base elevation of each polygon tank was the same at elevation 5 feet. As household tanks are fairly typical, all simplified tanks were therefore assumed to be 6 feet high. The diameter of the tank is driven by the combined volume of all household tanks located within the same service area—therefore, diameters of each simplified tank are variable. Various pipe diameters were modeled for the simplified connection pipe to the simplified tank to keep the same friction losses that the series of household tanks would have.

3.6.6. Population and Water Demand Allocations

The second stage of the network model development involved specifying water demands at each demand node. Water demands were identified and modeled to reasonably represent the actual water supply required to meet demands. The first step in the process of distributing the total water demand among the nodes was to determine the contributing service area for each node in the model. Demands of large volume water users were allocated to the nodes closest to the user.

As shown in Figure 19, water demands were allocated as follows:

(1) Designate water demand nodes (cyan dots) based on distribution network pipelines (pink lines)

(2) Use GIS tools to generate a water demand polygon (cyan lines) as the service area to be served by each node

(3) Calculate population, number of household and storage tanks, and the capacity within each polygon based on available GIS database

Using the available GIS databases (RMI 2010 and 2012), the population estimates were calculated and revised for the year 2010 and then projected to the year 2020 with a growth rate of 1.5% per year from 2010 to 2020.

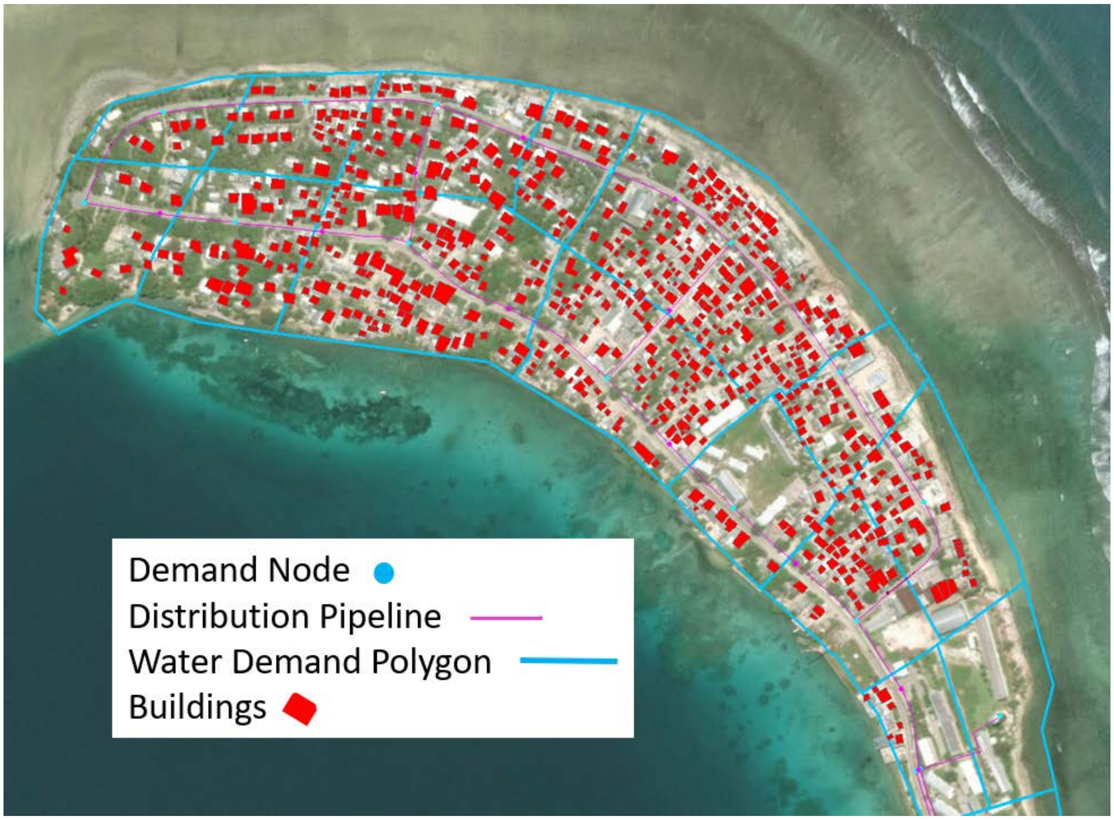

Figure 19: Sample of GIS application in water demand allocations.

With the service areas identified, demands were developed based on the population data. Figure 20 shows the 77 service areas generated for the DUD system. There are 38 service areas in the Laura groundwater subsystem.

Appendixes A through D contain the estimates and calculations of population, storage tank capacity, and the residential and commercial/institutional water demands in each of the service areas of the DUD and the subsystems modeled for the Existing Conditions and Improved Conditions Scenarios.

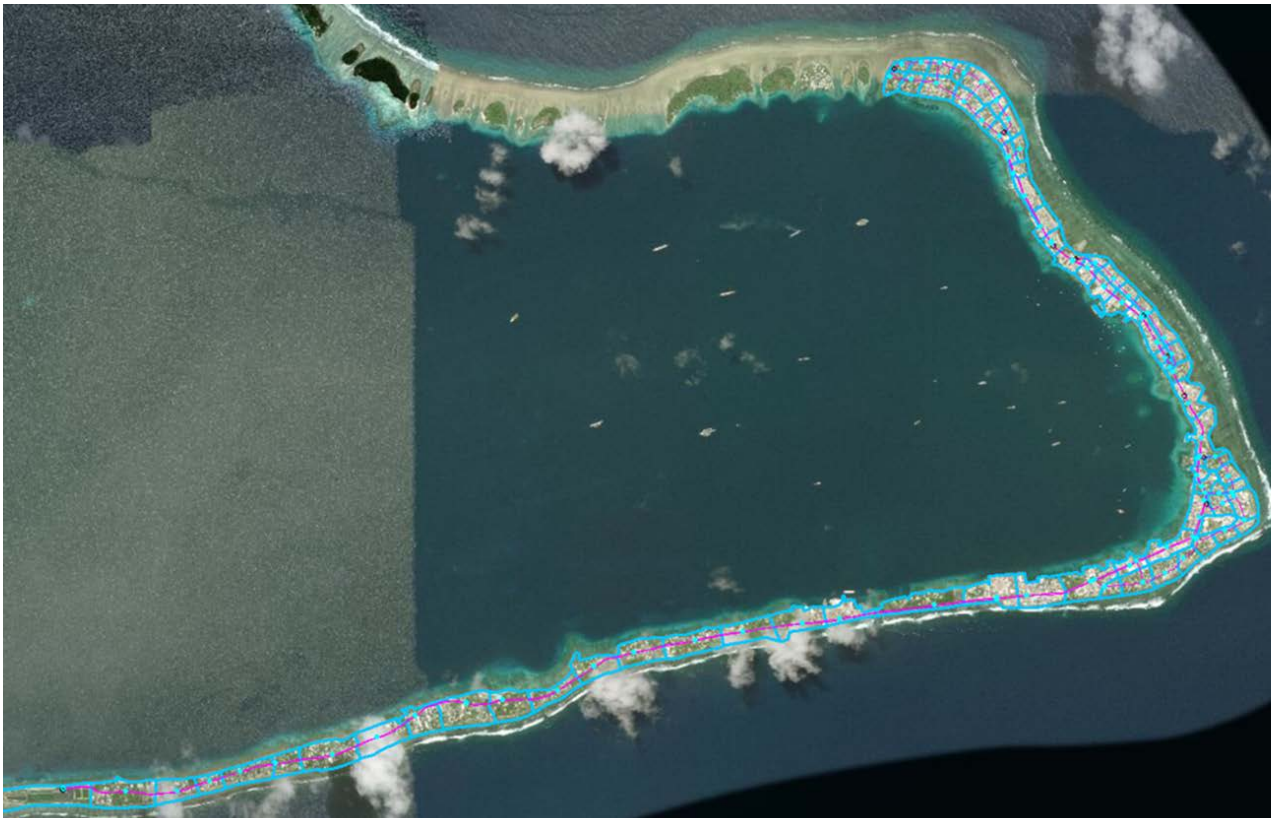

Figure 20: Seventy-seven service areas generated for the DUD system.

3.6.6.1. Demand Curve Assumptions

Current operation data is insufficient to generate a diurnal curve for residential use. The Improved Conditions Scenario assumes a typical diurnal curve for a small water system, shown in Figure 21. Note that the demand exceeds supply in both the Existing Conditions and the Improved Conditions Scenarios. The water user demand from the household tanks tends to be higher during the morning (about 7 a.m.), then peaks again in the evening (about 6 p.m.). A peaking factor of 1.75 was assumed.

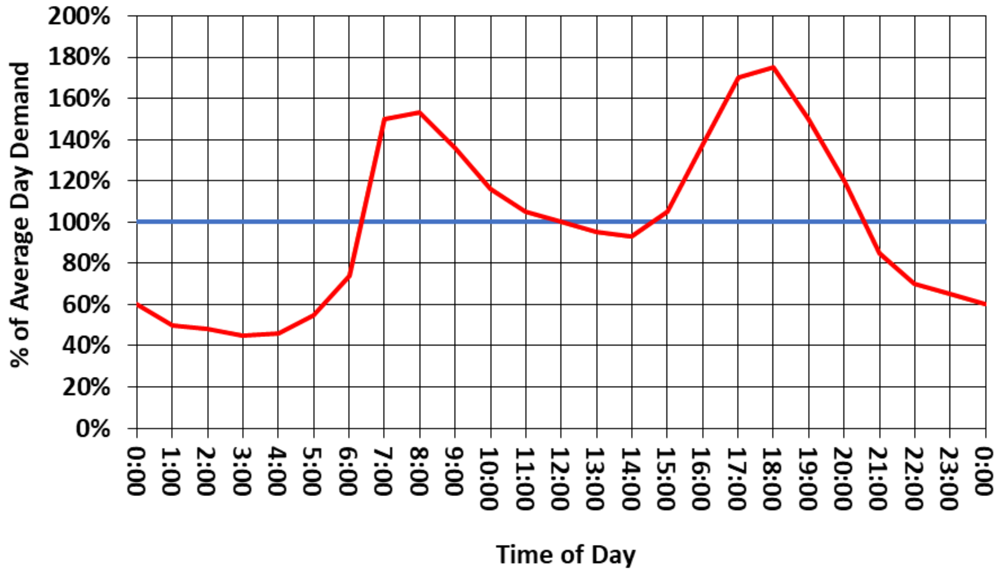

Figure 21: Typical diurnal curve for residential and hospitality connections.

A typical diurnal curve for commercial/institutional (school and office) buildings is shown in Figure 22. Water use peaks from about 8 a.m. to about 4 p.m.. A peaking factor of 2.4 was assumed.

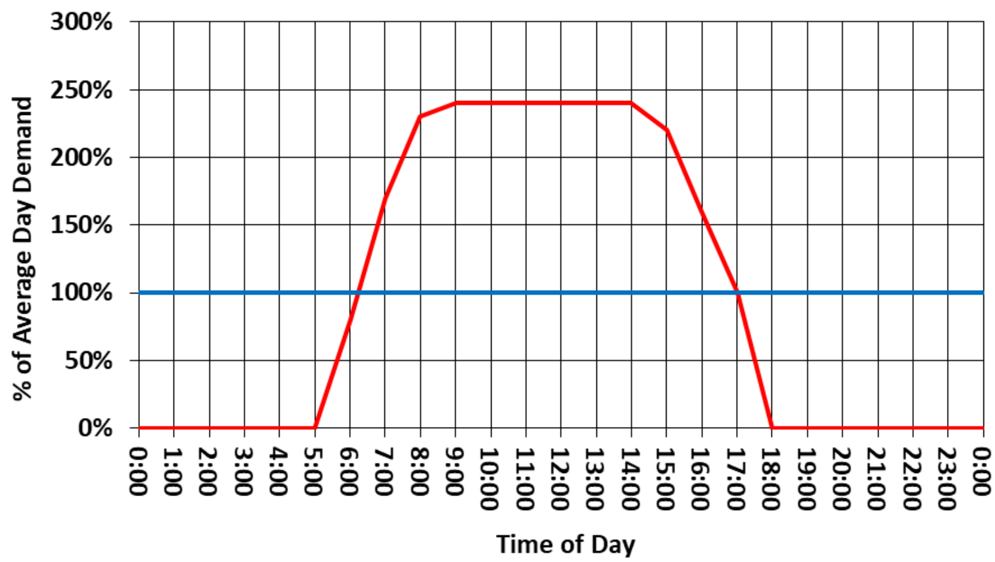

Figure 22: Typical diurnal curve for offices and schools.

3.6.6.2. Summary of Residential Water Demands

Appendixes A through D contain the estimates and calculations of population, storage tank capacity, and the residential and commercial/institutional water demands in each of the service areas of the DUD and the subsystems modeled for the Existing Conditions and Improved Conditions Scenarios. The appendices contain data and calculations as noted in Table 4.

Table 4. Location of Model Data for Water Demand Analysis

Spreadsheet Tabs	Existing Conditions Scenario	Improved Conditions Scenario
DUD Subsystem		
Basis: Details number of structures (residential and commercial) by polygon, 2010 census population by polygon, and 2020 population projections. Large water users, tank capacities, and number of connections are also included	**Appendix A**	**Appendix C**
Water Demand Summary: summarizes the data in the Basis tab.		
Laura Subsystem		
Basis: Details number of structures (residential only) by polygon, 2010 census population by polygon, and 2020 population projections. Tank capacities, and number of connections are also included.	**Appendix B**	**Appendix D**
Water Demand Summary: summarizes the data in the Basis tab.		

3.7. Future Data Collection

Existing system operation data has been requested. Operation data as shown in Table 5 would contribute to understanding the complete operation of the existing system. Once data is collected and integrated into the model, specific recommendations can be made for system improvements.

Table 5: Operation Data Request table. Add rows for any additional valves not included in the table.

Project Features		Clock Time							
		Open	Close	Open	Close	Open	Close	Open	Close
Pumps	Pump 1								
	Pump 2								
	Pump 3								
Valves	GV-TPCN								
	GV-X1X								
	GV-X2X								
	GV-X3X								
	GV-X4X								
	GV-X5X								
	GV-X6NA								
	GV-X6X								

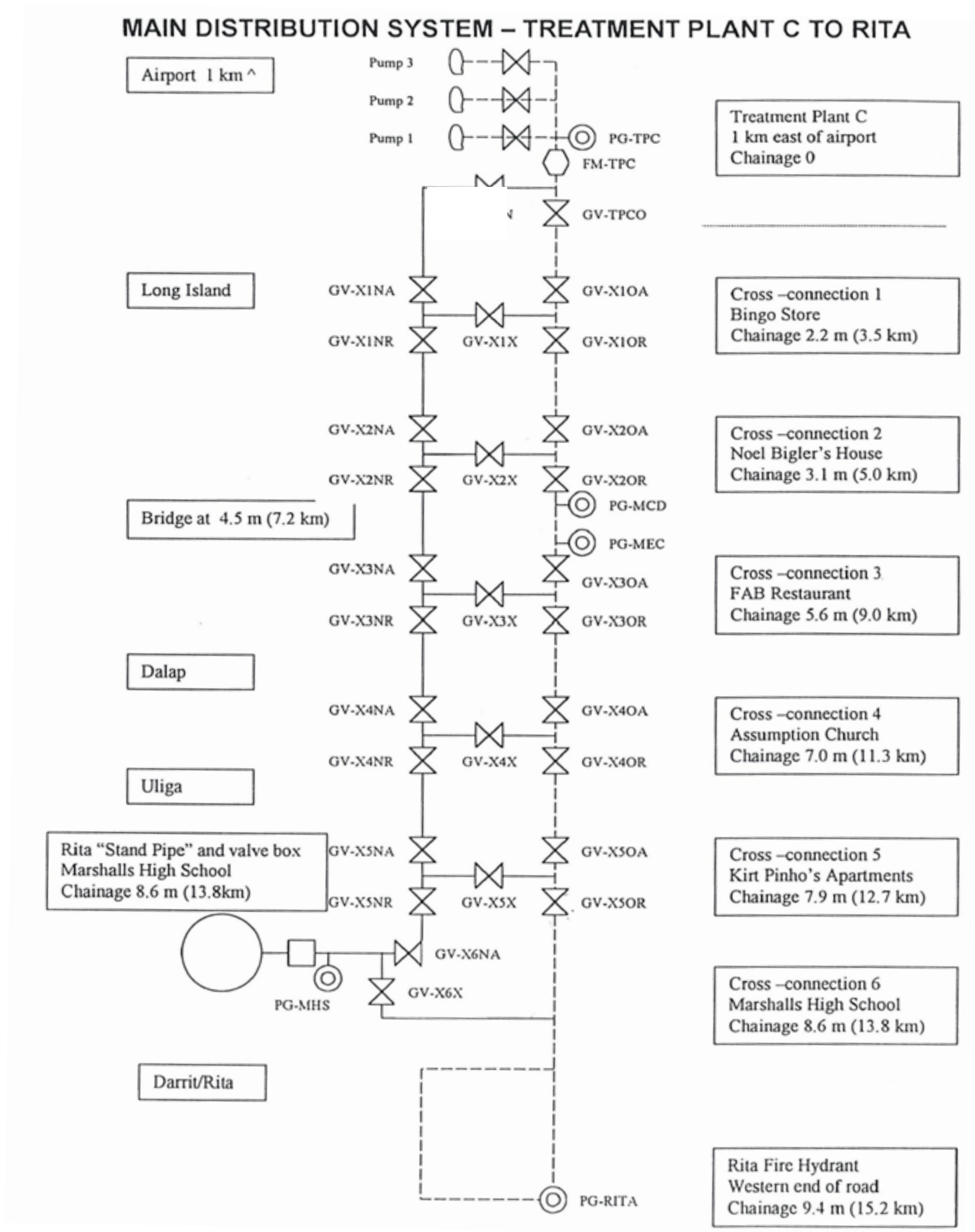

Figure 23: Schematic of valving associated with existing DUD system (Johnston 2013, used by permission, all rights reserved).

3.8. Hydraulic Model Calibration

Typically, model calibrations have an objective of verifying the Hazen-Williams C-Factor of the transmission main for accurately modeling friction losses in the pipeline. New pipes have higher, "smooth pipe" Hazen-Williams C-Factors. Old pipes have lower, "rough pipe" C-Factors. Calibration of the model would confirm where in that C-Factor spectrum the actual pipes are. However, both the

DUD and Laura transmission systems have very low velocities, so the impact of friction losses is not significant.

Significant drivers in model verification include the correct connectivity of the system, leakage detection, and identification of illegal connections.

4. Identified Deficiencies of Existing System

Based on the site visit and modeling results, Reclamation identified deficiencies in the existing municipal supply, storage, and distribution system.

4.1. Water Supply vs. Demand

Although the Existing Conditions Scenario model assumed that there was enough water supply to meet the demand, field observations and available data show that this is not the case. The Existing Conditions Scenario model is only a steady state model and does not reflect the intermittent operations.

As discussed in Section 1.2.2., many households do not have rainwater storage tanks, or rainwater collection is low due to missing gutters or improper piping arrangement.

Currently, the existing system relies fully on water from catchment at airport, off rooftops, as well as supplemental groundwater from the Laura system. In the dry season, raw water supply is limited and relies heavily on water stored in raw water reservoirs. Thus, there is not enough water supply during the dry season to fully operate the system continuously to serve the demand for all end users.

As the demand is greater than the supply, the DUD system can only operate on an intermittent basis. The limited supply of raw water means the MWSC operates DUD system intermittently, turning the system on three days per week from 4:30 p.m. to 8:30 p.m. Laura system was operated approximately during the hours of 8:00 a.m. to 4:00 p.m.

In wet season, users supplement their water supply with their own local water catchment systems. In dry season, users must purchase bottled water for home use.

4.2. Customer Connections

As discussed in Section 1.2.2., only a small percentage of the atoll’s population is connected to the system, as an estimated 80% are not connected. Based on MWSC estimates and discussions, about 800 users in the DUD system and 100 users in the Laura system are connected (Table 6). This leaves most of these populations without water service.

Table 6: Summary of Existing Connections

System	Currently Connected	Total Possible Connections	% Not Connected
DUD	800	3,853	79.2%
Laura	100	580	82.8%

4.3. System Water Losses

Data to model the amount of water lost to leaky pipes or nonrevenue connections is not available. The volume of water lost through leaking pipes is roughly quantified in a report by Asian Development Bank (2020). The level of nonrevenue water (NRW) in 2018 was estimated at 70%, of which two-thirds is estimated to be due to leakage from distribution mains and service connections. NRW that is not lost to leakage is generally lost to illegal connections to the system.

The Existing Conditions Scenario results confirmed the conditions reported by MWSC.

4.4. Model Results

The Existing Conditions Scenario model results show that if all end users were to connect to the system, the system would not be able to serve all connections.

4.4.1. Low System Working Pressures

For the Laura subsystem, the model confirms low pressures along the long transmission line, with little to no pressure availability as the water approaches the International Airport.

There is a high rate of system pressure drop over the long stretch of service areas from the airport to Rita. The Rita area at the end of the DUD system frequently gets little to no pressure. With no pressure, there is no water delivery. The Existing Conditions Scenario model results corroborate the low service pressures throughout the DUD system, as demonstrated in Figure 24.

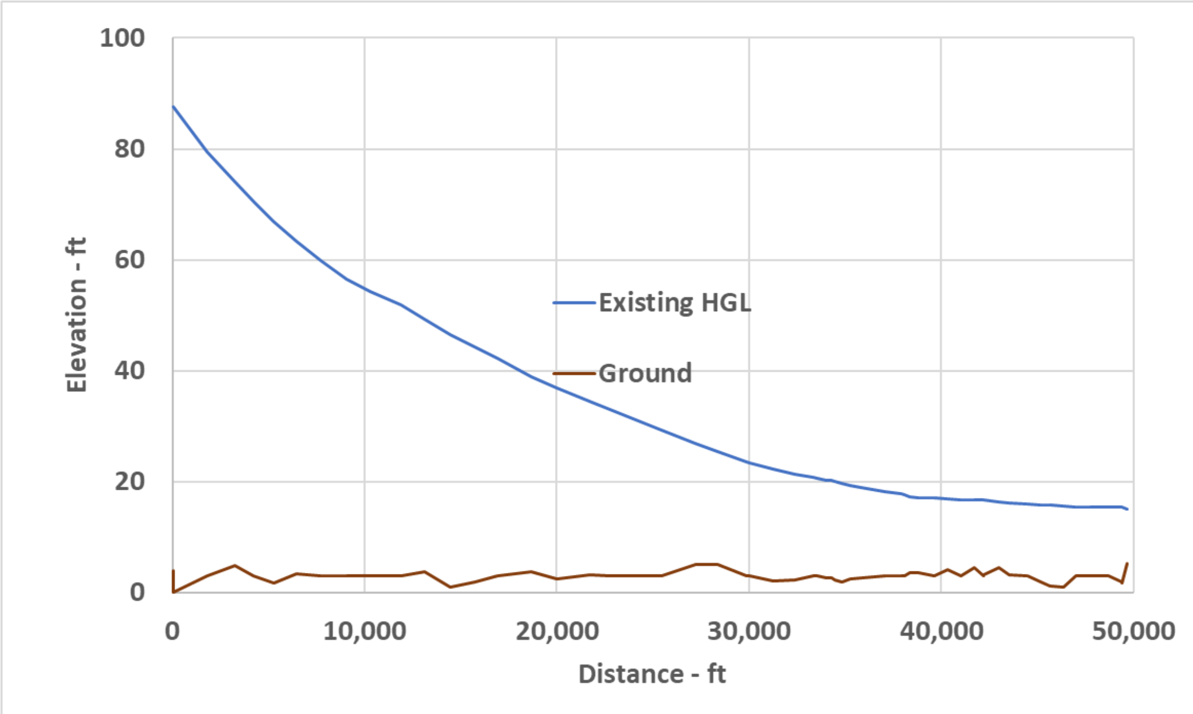

Figure 24: HGL and ground profiles in the Existing Conditions Scenario.

The model also confirmed the system's lack of capacity to fill the existing 400,000-gallon standpipe at the high school, due to insufficient pressures and lack of flow control throughout the system.

4.4.2. Variable Tank Filling

For the DUD system, the model confirms rapid filling of residential water storage tanks close to WTP C, and very slow or no filling of residential water storage tanks far from WTP C, in the Rita area. Tanks located near the WTP C Pump Station have high service pressure to fill the tank, shown in Figure 25. Note relatively quick filling of the tank in approximately five hours (HGL, blue), and rapid recovery when tank deliveries are made (flow, red). In contrast, tanks farthest from the WTP C Pump Station (Rita area) require nearly a day to fill (approximately 18 hours), and take longer to recover when deliveries are made (Figure 26).

Similar low system working pressure conditions are also encountered when modeling the Existing Conditions Scenario for the Laura groundwater subsystem.

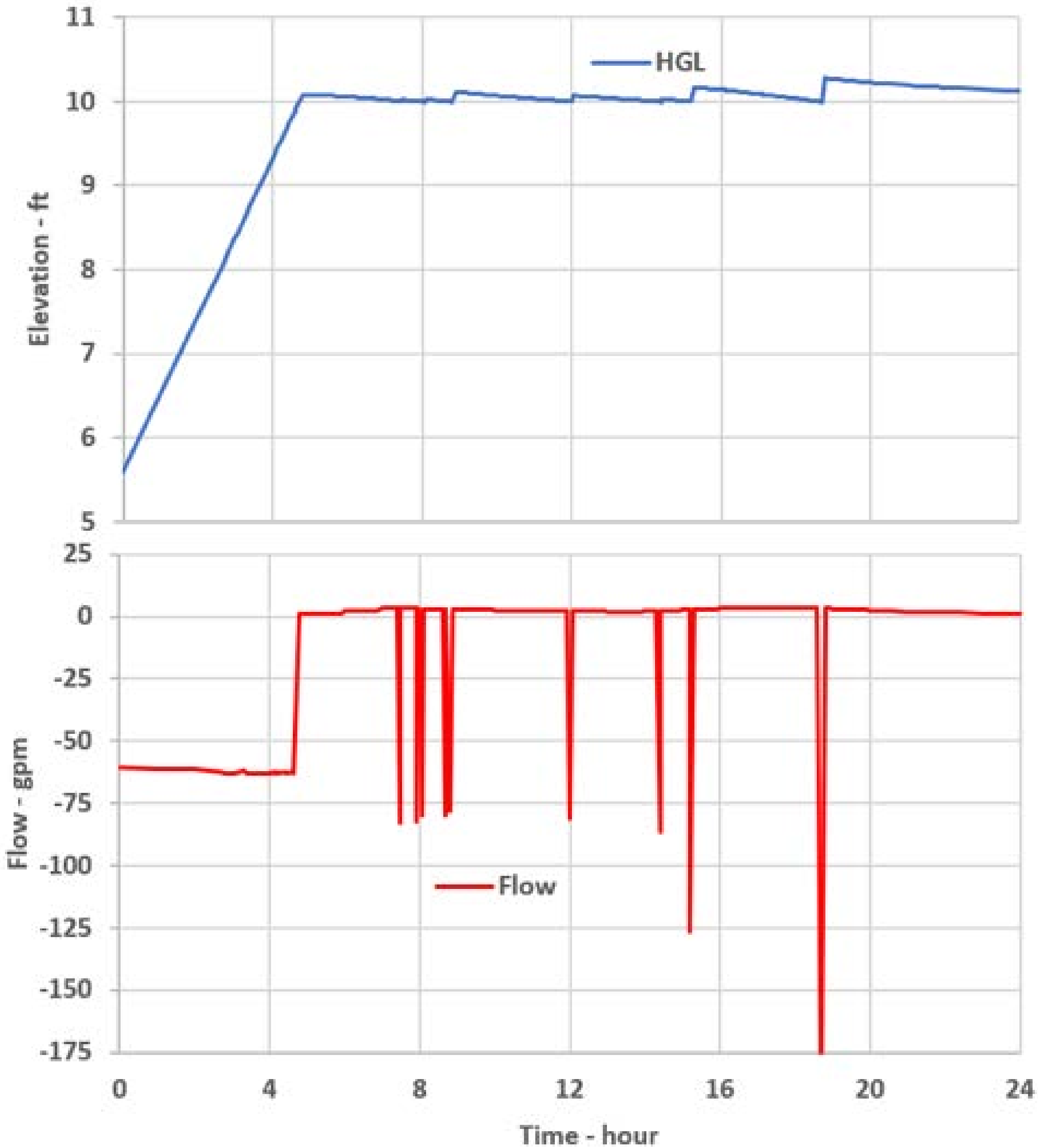

Figure 25: Typical tank filling and hydraulic grade line for a tank near the WTP C Pump Station.

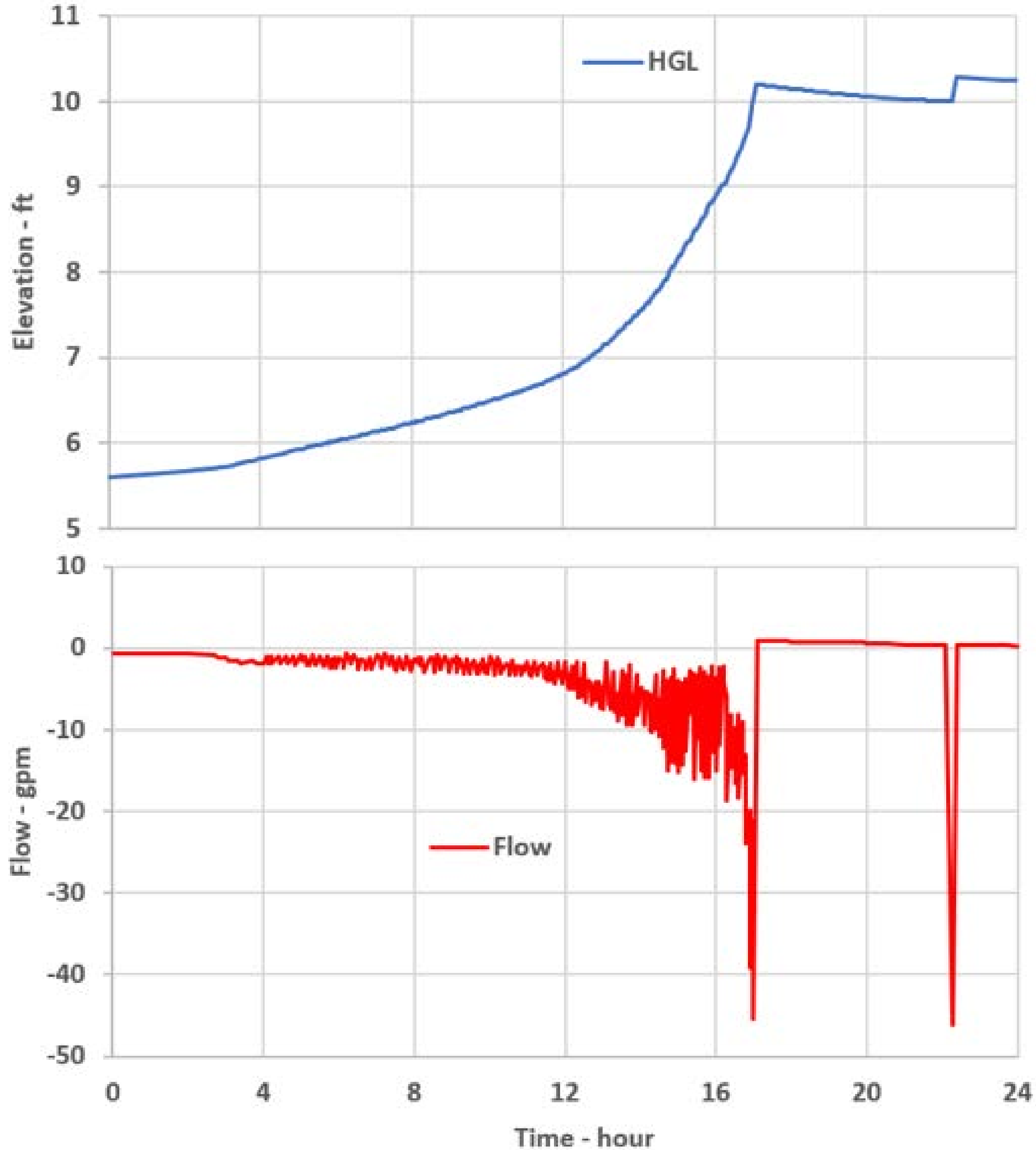

Figure 26: Typical tank HGL and flow shown for a tank far from WTP C Pump Station.

5. System Improvements

The recommended system improvements discussed in this chapter stem from the TSC site visit in January 2020, including discussions with the MWSC and the hydraulic evaluation of the existing system operation. See Section 6.2. *Conceptual Decision Matrix for Recommended System Improvements* for a ranked weighted score and notes.

Most of these actions can be installed independently of other solutions, and there is no particular order. Note that the new standpipe would depend on flow control valves and the installation of isolation valves to permit proper operations. In general, the improvements that will provide the most benefit are:

- Installing flow control valves provides the best cost benefit as it is relatively inexpensive, benefits all users, and would allow the system to operate more uniformly and efficiently.

- The combination air valve at the bridge would removes trapped air at the high point of the system, allowing water flow.

- The system downstream of the ductile iron pipes at the bridge depends entirely on the pipes, so repairing these pipes before they break is imperative.

- Although repairing pipe with CIPP, is expensive and therefore ranked low, the benefit is very high—as this will prevent breaks, joint leaks, and improve water quality.

Capital improvements to the system will be planned in phases as priorities and funding availability allows. TSC's continued scope of work for the Majuro Water System Master Planning Study will provide recommendations for improvements in phases into the year 2040.

5.1. Improvements Incorporated in the Improved Conditions Scenario

5.1.1. Provide Rainwater Household Storage Tanks

According to the Majuro Household Water Survey Report (RMI 2010), 79% of RMI residents rely on rainwater collection as their drinking water source while 1,309 households have no rainwater storage tanks.

The lack of access to water at the household level could be a significant contributor to high rates of water-borne illness.

TSC recommends installing a 1,200-gallon household rain catchment and water storage tank system for all households without rainwater storage tanks, or with a tank capacity less than 1,000 gallons. It is estimated that about 1,500 storage tanks would be needed. To improve overall system operations, it is also recommended that when any new household rain catchment and water storage tank system is installed that a flow control valve (see Section 5.1.7). be required.

5.1.2. Replace Ductile Iron Pipes at Bridge

Ductile iron pipes rather than asbestos-cement pipes were used to cross Majuro Atoll's main bridge. Due to the corrosive atmosphere, these ductile iron bridge crossing pipes are corroded and in poor repair. Temporary wrapping has been applied at joints to mitigate the leakage, shown in Figure 27.

This segment of pipe needs to be replaced as soon as possible to prevent a potential pipe failure, which would completely shut down the transmission main for a long time.

Figure 27: Ductile iron pipe with wrapped joints at bridge crossing.

5.1.3. Use Cured-In-Place-Pipe for all Asbestos-Cement Pipes

Current DUD water supply and distribution system uses these asbestos-cement pipes:

- 10,000 feet of 6-inch diameter
- 4,000 feet of 8-inch diameter
- 8,000 feet of 10-inch diameter
- 35,000 feet of 12-inch diameter

Asbestos-cement is a material made from asbestos fibers, cement, and water that was used to manufacture pipes for water networks up until the 1980s until the health hazards associated with asbestos became well known.

Most of the asbestos-cement pipes were installed in the 1970s and have reached the design life expectancy of 50 years. These pipes need to be renewed to prevent deterioration which will result in impaired water quality, reduced hydraulic capacity, and higher leakage rates. Traditional trenching and replacing asbestos-cement pipes are costly and hazardous. The digging will set fibers free in the air. Construction workers could inhale these fibers—causing pulmonary irritation and possible respiratory diseases.

Trenchless technology is the most common approach to resolve asbestos in water pipeline. The three most commonly used trenchless methods are: pipe bursting, sprayed-in-place pipe and cured-in-place pipe (CIPP). CIPP, placing a new lining inside the existing pipes, is recommended to renew the asbestos-cement pipes for the DUD system. Linings are inserted into the existing pipe without exposing workers to harmful fibers. Once installed, the lining hardens and offers a smooth, clean interior for conveyance of water (Figure 28). The lining will also strengthen the structural integrity of the existing asbestos-cement pipes and significantly reduce the leakages. Asbestos from the existing pipe cannot penetrate the lining.

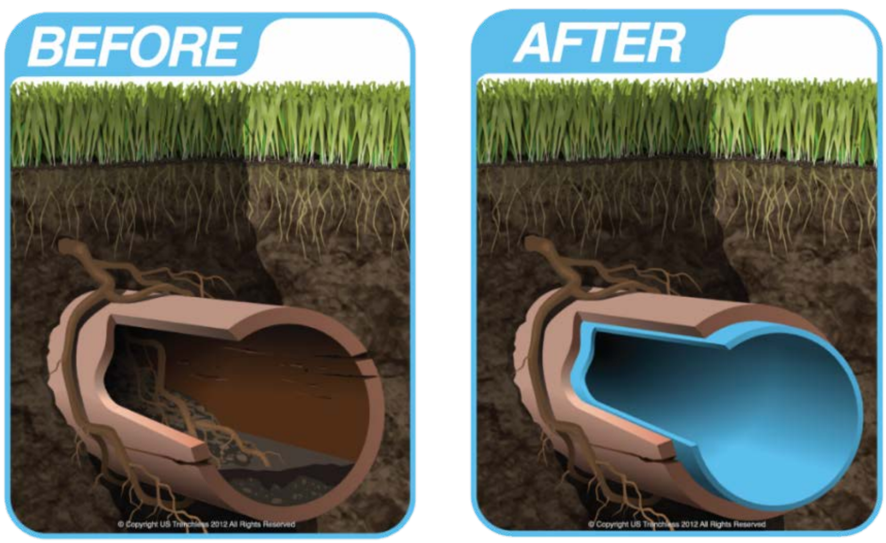

Figure 28: New lining could be installed in existing pipes (Drawing courtesy of U.S. Trenchless [2020], all rights reserved).

5.1.4. Install a New 400,000-Gallon Standpipe

A standpipe with a storage volume of about 400,000 gallons close to the Marshall Islands High School campus was constructed in the MWSC system improvement program in 1999 to provide needed working pressure for the Rita area. However, there is not enough system pressure to fill the standpipe, and the standpipe was abandoned.

Due to corrosion and deterioration, the standpipe is not safe for use and is beyond the possibility of restoration.

TSC recommends dismantling and removing the existing steel standpipe and replacing it with a concrete standpipe with anti-corrosion coating to protect the standpipe from the corrosive environment.

To have enough system pressures to fill the proposed concrete standpipe, flow control valves to all household storage tanks should be installed before constructing a new concrete standpipe.

The new concrete standpipe would need to have an orifice plate or other flow control device to limit the flow when filling the standpipe. During the low-demand periods in the Rita area, excess flow would fill the standpipe. During the high-demand periods when the system pressure in the Rita area is lower than the pressure head inside the standpipe, flow would be discharged by gravity from the standpipe to supplement the demands of the Rita area. Figure 29 shows how standpipes work. Figure 30 shows the filling and emptying of the standpipe after integrating to the improved DUD system.

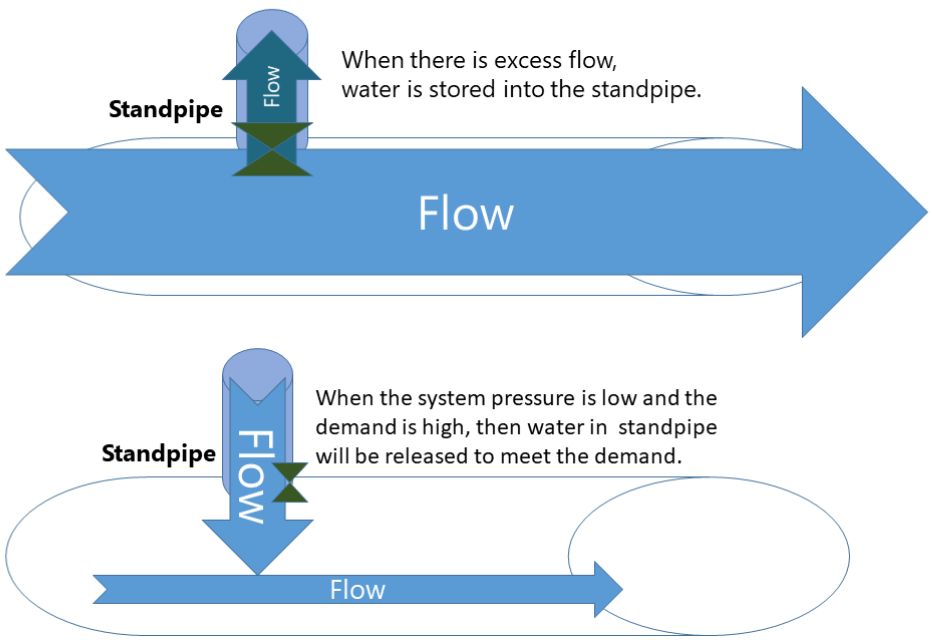

Figure 29: Conceptual drawing of standpipe functions.

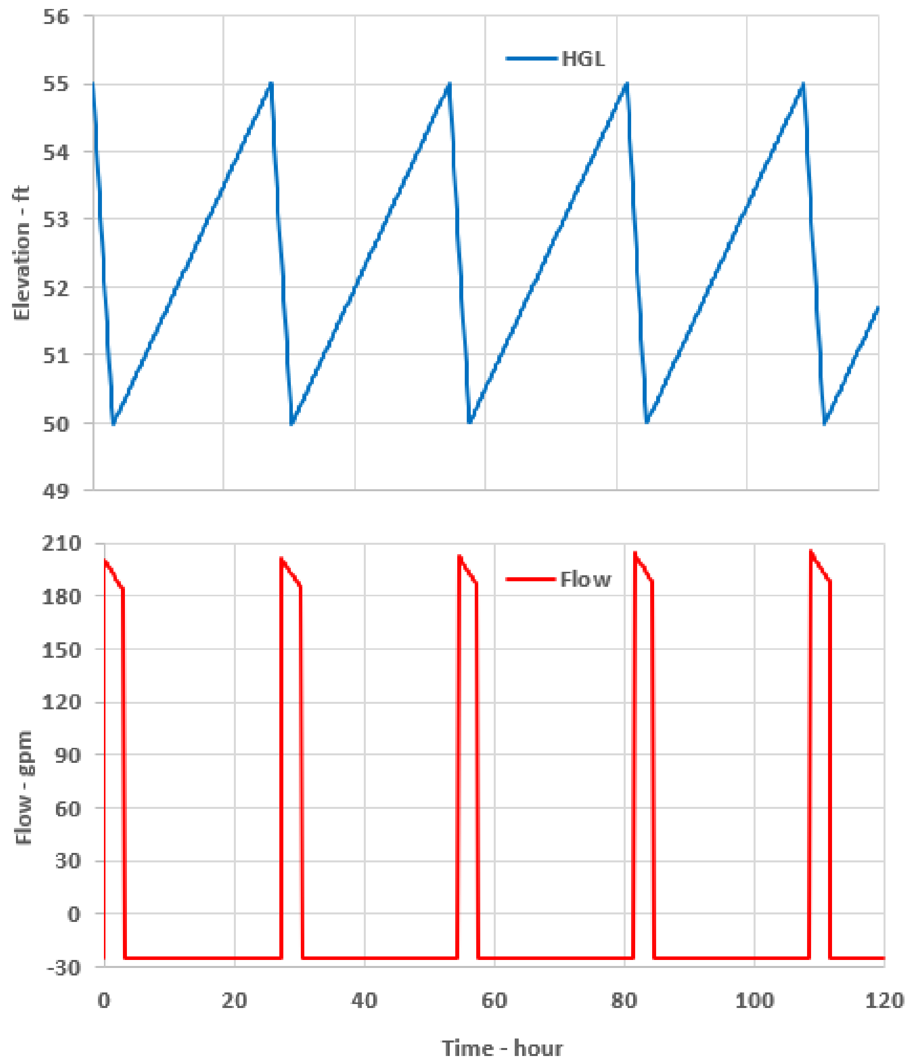

Figure 30: HGL and flow fluctuation pattern of the recommended 400,000-gallon standpipe.

5.1.5. Install an Air Valve at the Bridge

In a pressurized pipeline system, a combination of air release valves and air vacuum valves, or blowoffs are needed for pipelines to function efficiently. Without these valves, air pockets build up inside the pipeline and can reduce pipeline flow capacity by 5 to 10 percent or more (Figure 31). The system pumps must work harder to overcome the constricted flow. Releasing air pockets will improve pumping efficiency.

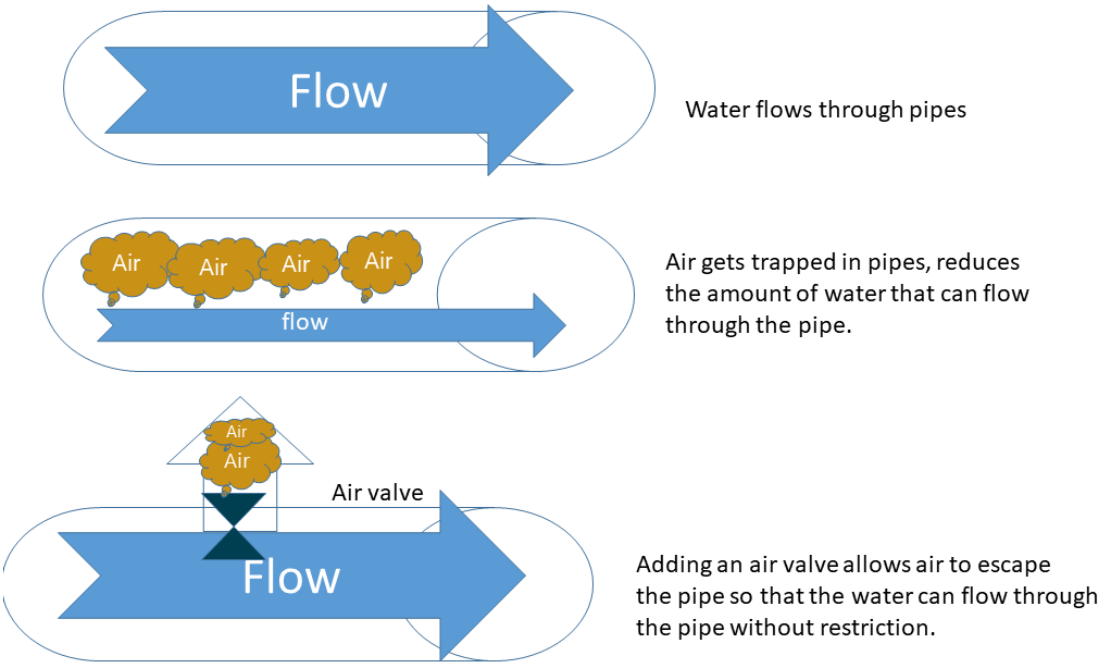

Figure 31: A conceptual explanation of air vent functions.

Air valves are generally installed at the high points of the pipelines where the air tends to accumulate. For the DUD system, the only noticeable high point is at the bridge. Because installing an air valve at the high point of the middle of the bridge span would be difficult, TSC recommends installing a combination air valve on the ascending stretch near the abutment of the bridge (Figure 32).

Figure 32: Place an air valve at the bridge abutment, rather than the actual high point.

5.1.6. Install Flow Control Valves on the Main Pipeline

Water follows the path of least resistance. In the Majuro system, this path of least flow resistance is from the pumping station at WTP C to those water storage tanks located near the pump station. Currently, as water is pumped to Rita from WTP C, system pressures along the transmission mains falls rapidly due to the uncontrolled flows to water storage tanks located near the pump station. A flow control valve should be installed on the inlet pipe to the tank to control the rate of discharge to the tank, shown in Figure 33. With flow control, pressure drops along the transmission mains at a lower, controlled rate. This results in more uniform tank filling for all users of the system, regardless of whether they are near or far from WTP C.

Without flow control valves, water storage tanks far from the pump station receive low flow and pressure, but flow control valves throughout the pipeline can provide a consistent pressure so that tanks at the end of the line can be filled efficiently (Figure 34).

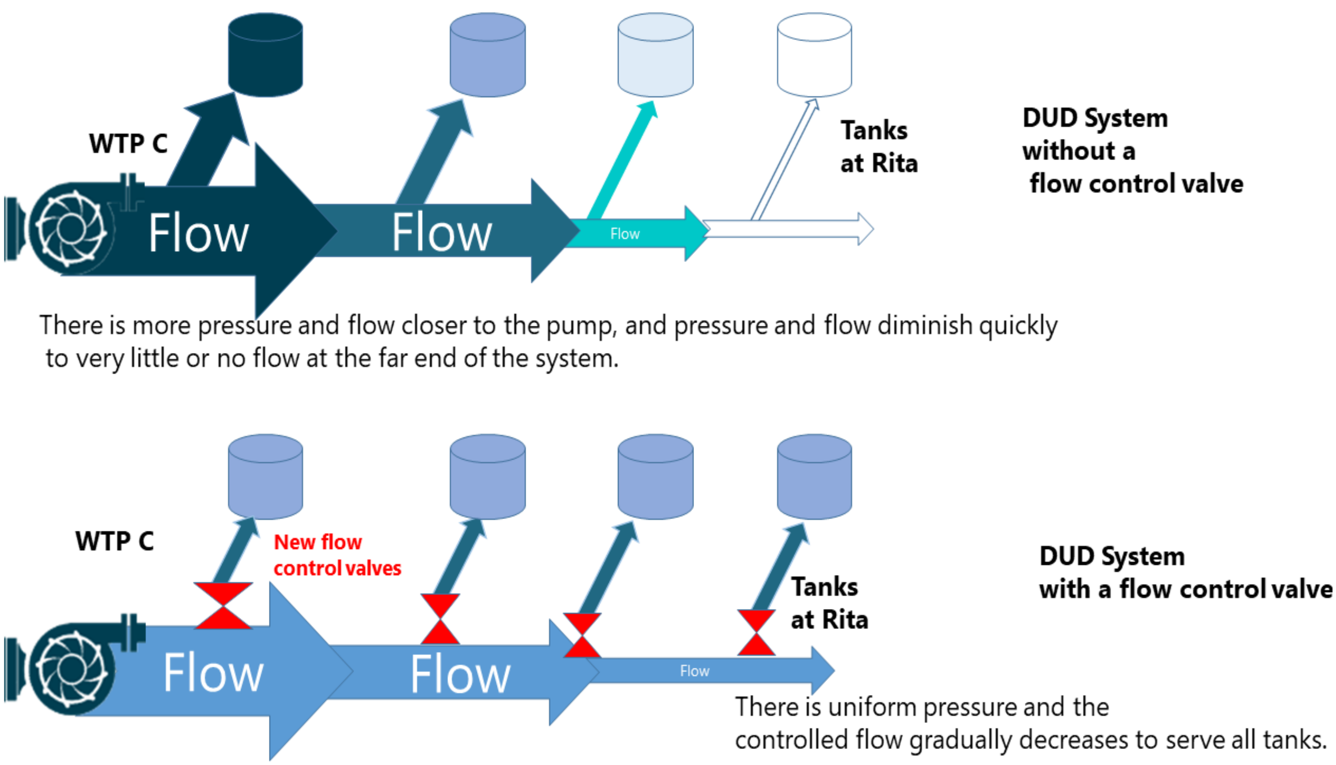

Figure 33: Flow and pressure conditions without (Existing Conditions Scenario) and with (Improved Conditions Scenario) flow control valves.

In the Improved Conditions Scenario, flow control valves are incorporated to all water storage tanks in the DUD and Laura subsystems. Figure 34 shows the improvement in the hydraulic grade lines (HGL) for the DUD and the Laura subsystems, respectively.

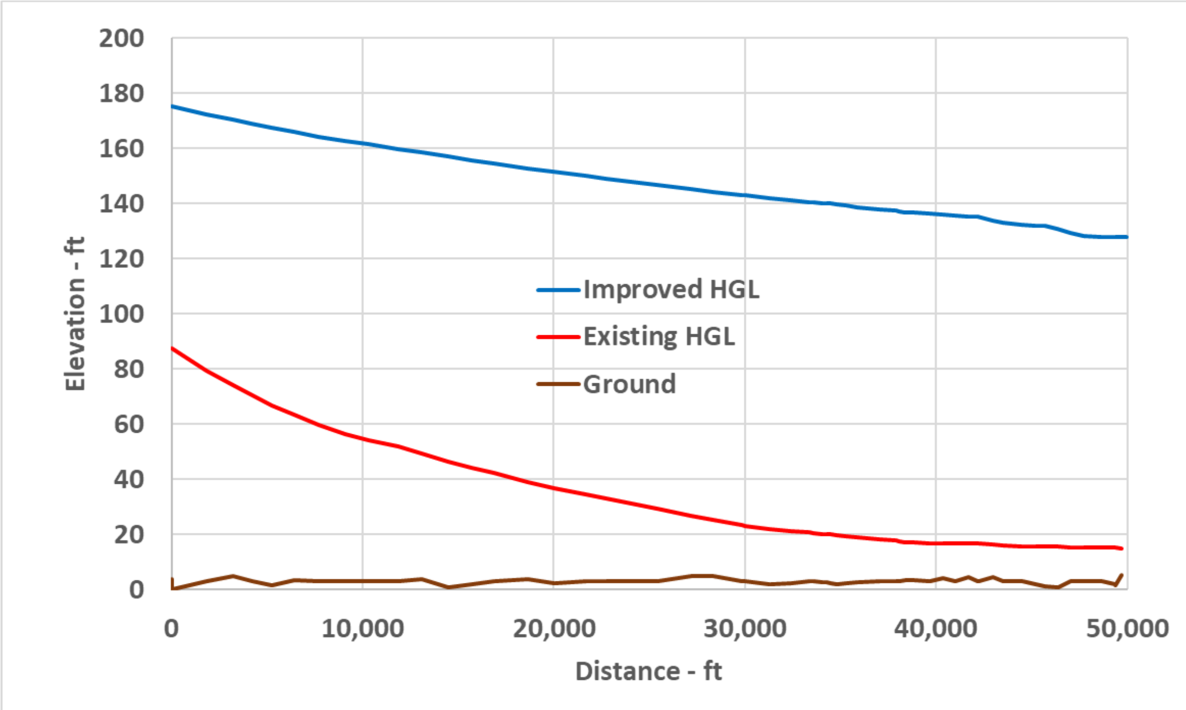

Figure 34: Comparison of HGL profiles of DUD system with and without flow control valves.

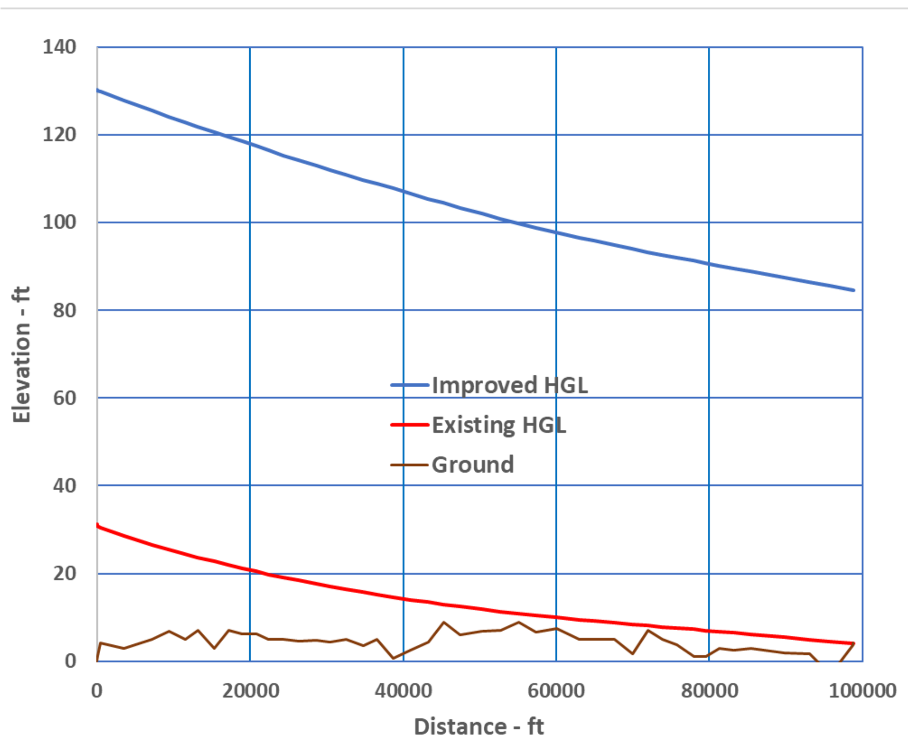

Figure 35: Comparison of HGL profiles of Laura subsystems with and without flow control valves.

Figure 36 through Figure 38 depict the Extended Period Simulation (EPS) results of the filling and emptying water at a tank near WTP C, a tank located at Rita and the tank at the government complex, respectively. The EPS was carried out with the system in the Improved Conditions Scenario for a period of 120 hours. As shown in these graphs, the systems have sufficient working pressure to meet the demands with the patterns of diurnal curves—regardless of the tank locations.

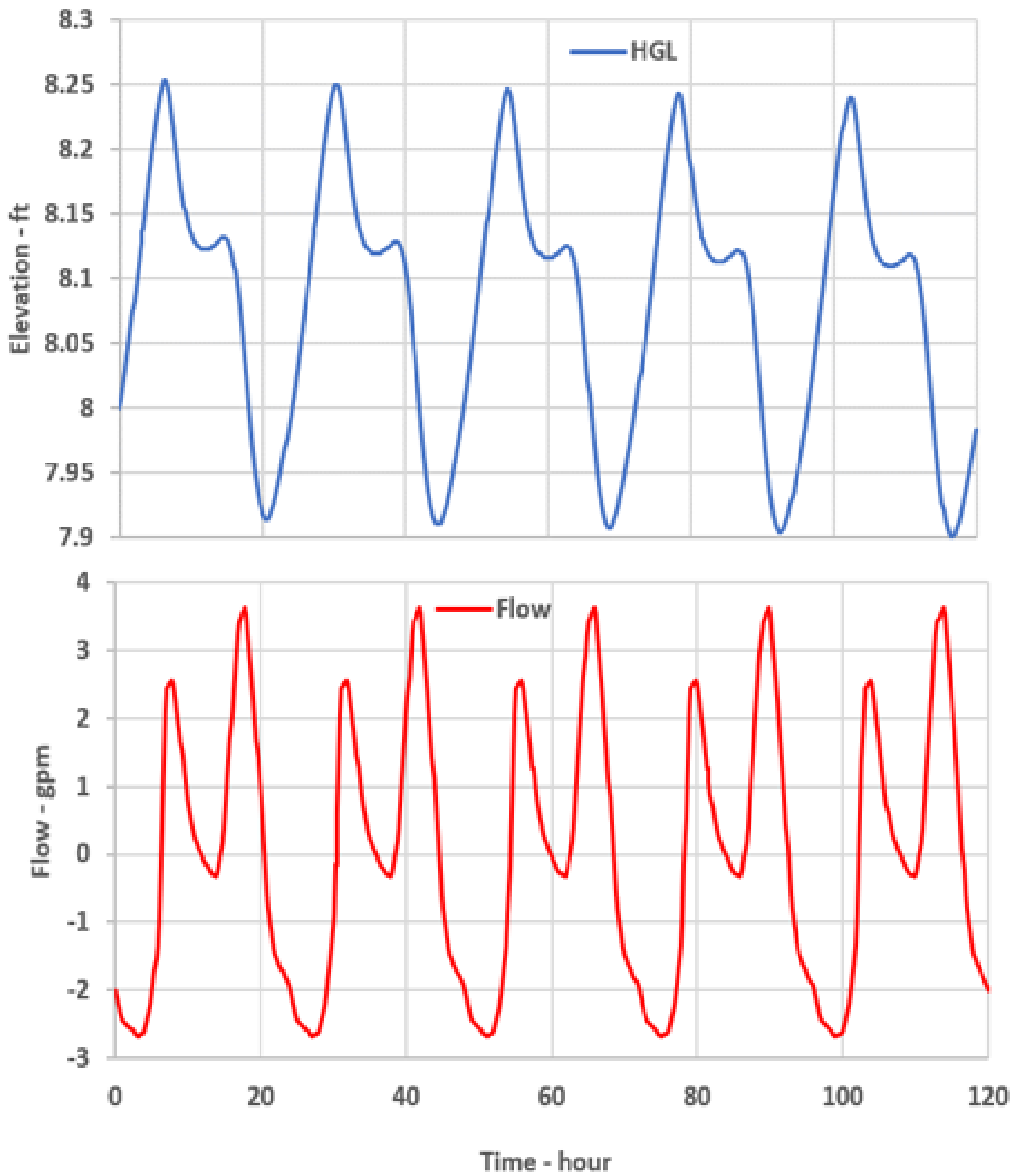

Figure 36: HGL and flow fluctuation pattern of a tank near WTP C.

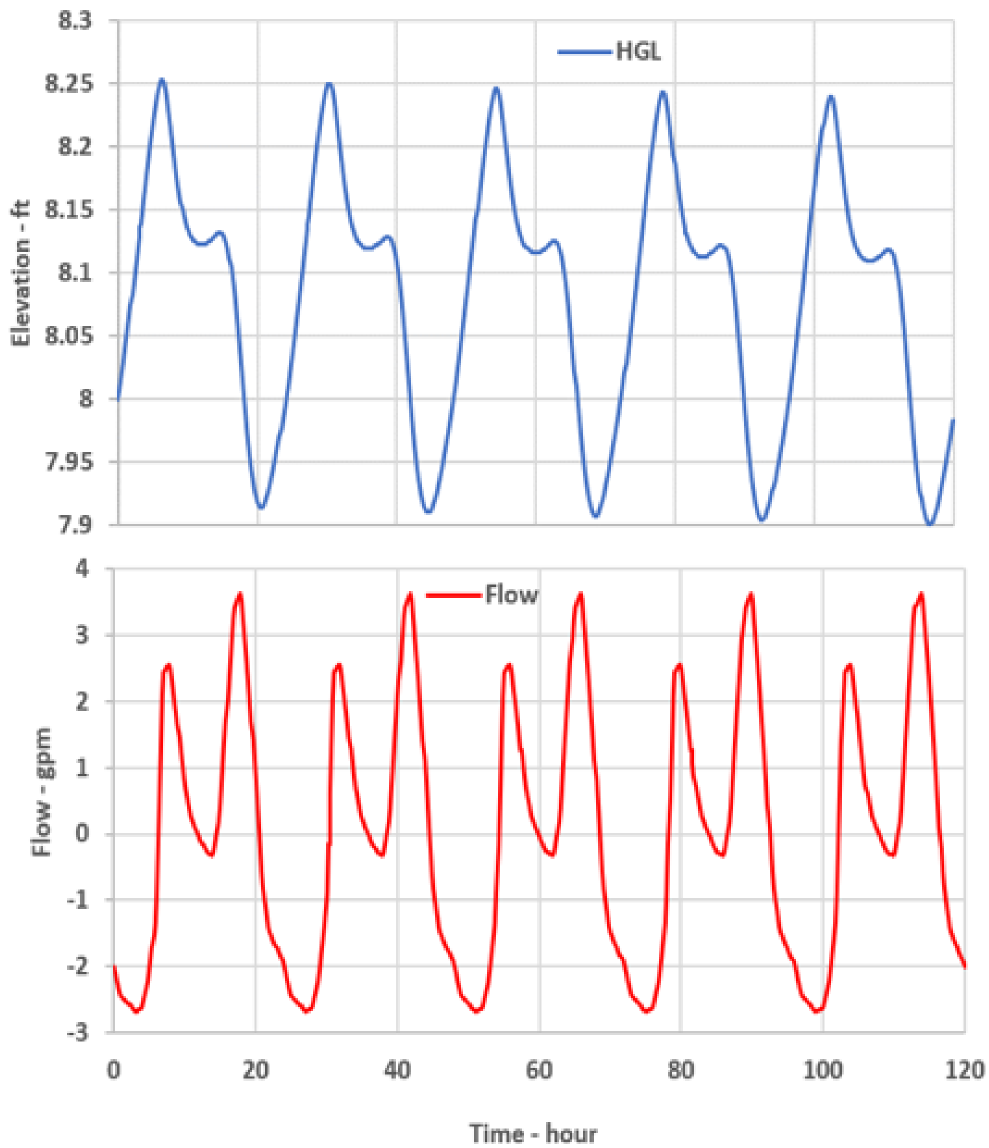

Figure 37: HGL and flow fluctuation pattern of a tank in Rita.

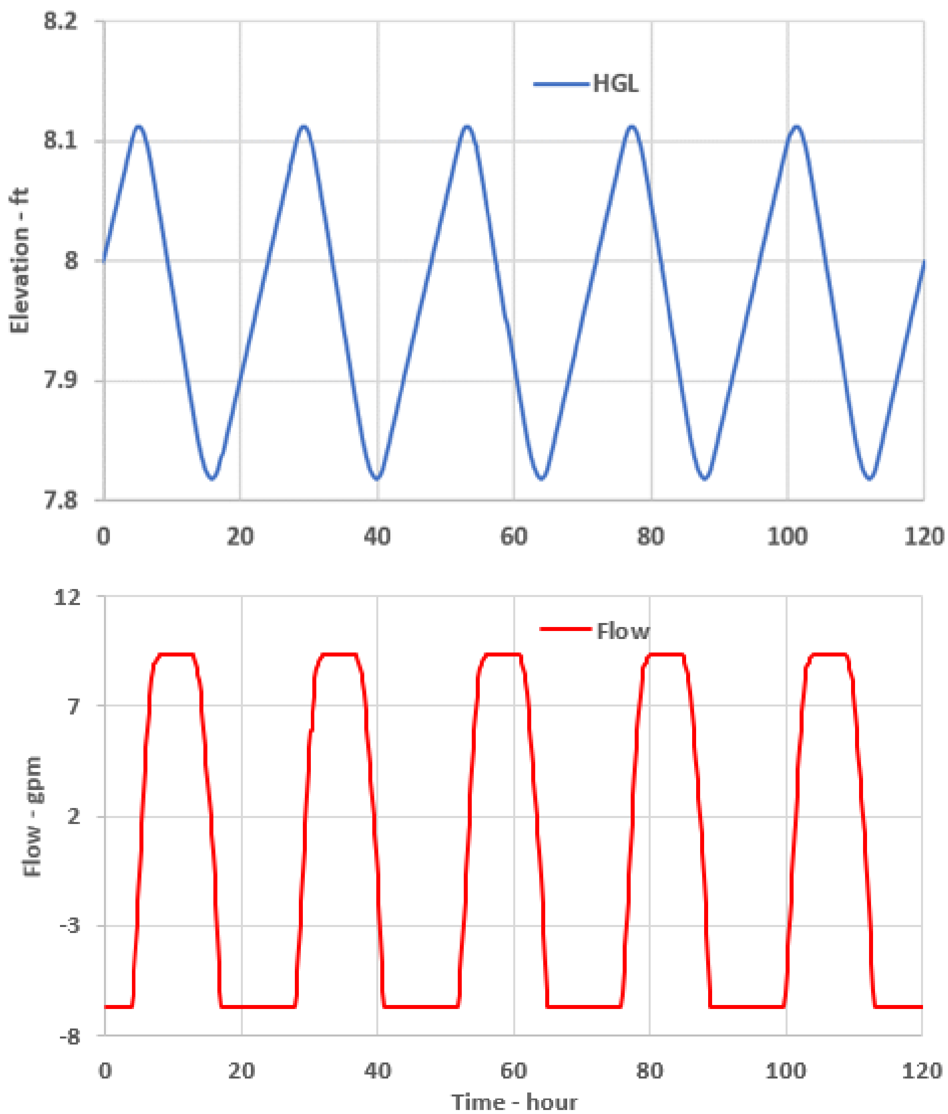

Figure 38: HGL and flow fluctuation pattern of the tank at government complex when the tank is connected to system under the Improved Conditions Scenario.

5.1.7. Install Flow Control Valves in Each Storage Tank

There are over 2,300 storage tanks in the DUD area with capacities ranging from several hundred gallons to more than 10,000 gallons, serving over 3,800 households. Water is delivered from the transmission main, then through the 2-inch lateral distribution pipelines and eventually via 1-inch or ¾-inch inlet pipes to the storage tanks (Figure 39).

Installing individual flow control valves on each tank supply line would provide a significantly improved pressure distribution across the entire MWSC network.

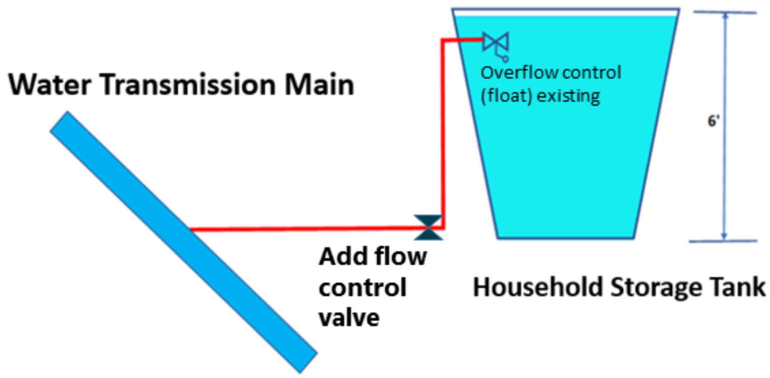

Figure 39: Added flow control valve for a household storage tank.

5.1.8. Install a Pressure Sustaining Valve at the Laura Pipeline to Airport Reservoirs

The groundwater system serves the Village of Laura via seven wells, and with a connection to the airport reservoirs to supplement the airport system as needed. The Laura groundwater subsystem has about 20 miles of water pipelines.

A pressure sustaining valve and orifice plate (or a similar device) installed on the pipeline at the exit to the reservoir at the airport would maintain the minimum pressure at the transmission main at a pre-defined value, as shown in Figure 40. Without the pressure sustaining valve, the pressure in the vicinity upstream of the reservoir drops to the water surface level of the ground reservoir.

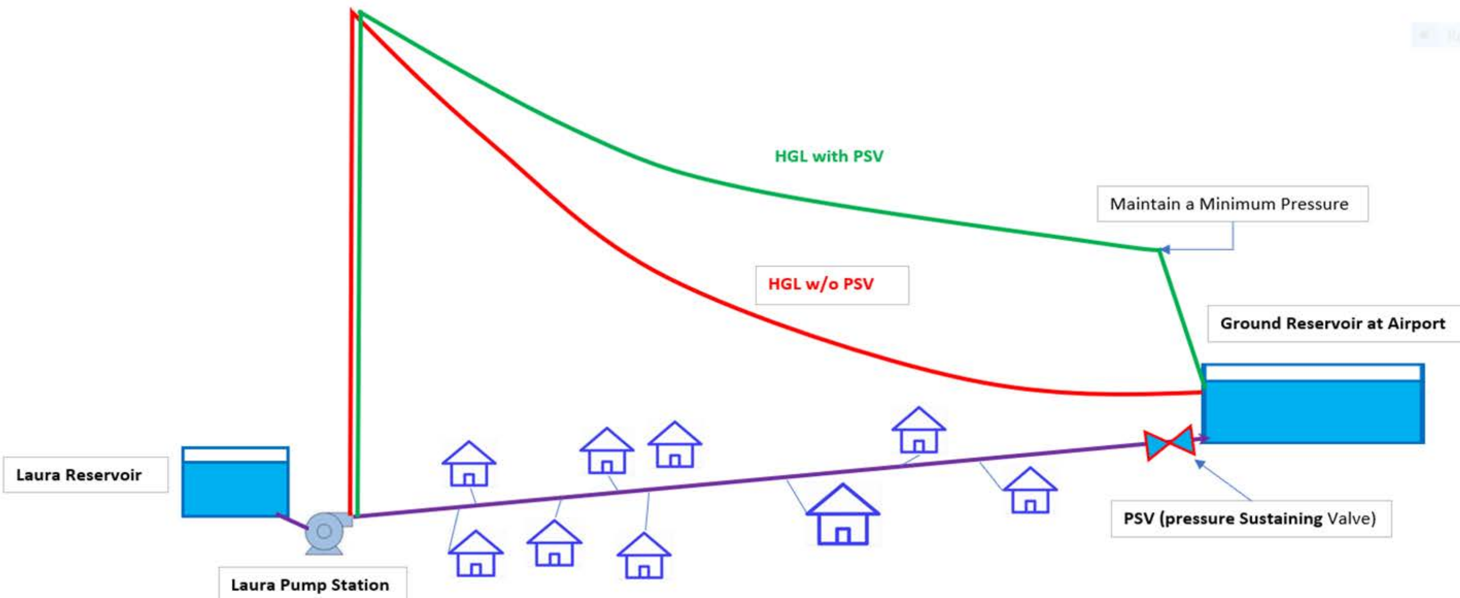

Figure 40: Comparison of HGL profiles of Laura's system with (green) and without a (red) pressure sustaining valve (PSV).

5.2. Other Improvements Not Included in the Improved Conditions Scenario

5.2.1. Install Public Standpipes

Installing public standpipes in economically depressed areas may generate extra revenue for MWSC, minimize the number of illegal connections, and provide convenient access for residents to obtain safe water. A public standpipe is a public spigot that provides about 5 gpm. This could be coin operated and could have safeguards to ensure that water is not wasted. Figure 41 shows one example of a public standpipe.

Figure 41: Public standpipes (photo used is courtesy of Uladzimir under a Creative commons license).

5.2.2. Develop a Rainwater Reservoir at Bokiur Island

Ejit, a small island with a population of about 300, is about 1,500 feet west of the shore of Rita (Figure 42). Utility lines have been installed from Rita to serve the island. During severe drought conditions, water has been delivered to the island by water tankers from the Majuro Atoll.

Bokiur Island is about 300 feet to the east of Ejit. The island is stripped bare of vegetation. An antenna tower is in the middle of the island. Bokiur has enough space for a reservoir 290 by 180 feet (Figure 43). The full storage capacity could be reach 3.5 million gallons at a depth of 10 feet.

The Bokiur reservoir would be able to serve Ejit residents and have excess capacity to supplement the water demands of the DUD system, particularly during a prolonged drought season. Water sources could be rain collection or groundwater if testing proves sufficient storage in available in the lens.

Figure 42: Aerial view of Bokiur Island.

Figure 43: Bokiur Island ground reservoir site.

5.2.3. Improve the Hospital Reverse Osmosis System

Safe and adequate water is essential for effective hospital health care operation and infection control, including washing surgical tools and equipment to creating comfort and safe environment for patients. World Health Organization (WHO) guidelines state that the minimum water requirements for a hospital is about 50 liters (13 gallons) per person per day. The saltwater pump that provides flow to the reverse osmosis units needs significant repair, or possibly even replacement. Currently some of the pump stages are not working and require further investigation to determine whether maintenance or replacement is the best improvement.

Currently, three 3 RO units provide portable water for the Majuro Hospital's surgical ward. Additional RO units are recommended to be installed in the hospital system. The RO system should have the capacity to meet the current regular water demands, as well as future 2040 demands.

5.2.4. Provide an Elevated Tank for Laura System

The current Laura water delivery system uses the method of direct pumping. Direct pumping requires less capital costs than using an overhead storage tank. However, there are significant drawbacks in direct pumping. Although systems with elevated tanks are more expensive to build, they can be less expensive to run. A pump in a system with an elevated tank will operate near its best efficiency points and then shut off. The elevated tank will maintain the design pressure for the system, saving significant energy and costs. Conversely, a direct pumping system runs constantly (24/7), and it is very difficult to keep the pumps running efficiently over a wide range of flows.

During power outage and other emergencies, the elevated tank system can meet required flow demands, while the direct pumping system could only do so if it is equipped with an emergency power generating system—which is costly to install and has high operation and maintenance costs.

6. Conclusions and Recommendations

While a water system that provides treated water 24 hours a day may not be possible. The improvements noted in Section 6. *Improvements* would significantly increase the level of service—serving populations who are currently unserved or underserved. Some improvements will have large impacts on system operations and reliability with minimal capital expenditures (e.g., installing flow control valves on all tanks, installing combination air valve at the bridge, and repairing the ductile iron pipes at the bridge).

6.1. Scenario Results

The Existing Conditions Scenario confirmed the conditions reported by MWSC. For the Laura subsystem, the model confirms low pressures along the long transmission line, with little to no pressure availability as the water approaches the International Airport. For the DUD system, the model confirms rapid filling of residential water storage tanks which are in close proximity to WTP C, and very slow or no filling of residential water storage tanks far from WTP C, in the Rita area. The model also confirmed the system's lack of capacity to fill the existing 400,000-gallon standpipe at the High School, due to insufficient pressures.

The Improved Conditions Scenario assumes sufficient water supply to run the system 24/7. For the Laura System, the Improved Conditions Scenario applies a Pressure Sustaining Valve upstream of the discharge to the airport raw water storage reservoirs. For the DUD System, the following improvements are incorporated:

- applying flow control valves at residential storage tanks,
- installing cured-in-place pipe (CIPP) solutions in all concrete-asbestos pipe sections,
- repairing the ductile iron pipe at the bridge,
- installing the air/vacuum release valve at the bridge (system high point), and
- replacing the 400,000-gallon standpipe at the high school

Installing public common-area standpipes, the rainwater reservoir at Bokiur Island, an additional hospital Reverse Osmosis system, and additional household rainwater catchment storage tanks are not included in the Improved Conditions Scenario.

The Improved Conditions Scenario model results demonstrated key improvements as shown in Table 7.

Table 7. Key Improvements Modeled in the Improved Conditions Scenario

Variable	Existing Conditions Scenario	Improved Conditions Scenario
Laura End-User Pressure	< 10 psi pressure, occasionally 0 pressure.	53 psi higher pressure, sustained
DUD End-User Pressure	< 10 psi pressure, occasionally 0 pressure. Residential storage tanks take upwards of 16 hours of continuous pumping to fill completely.	35 psi higher pressure, sustained. Residential storage tanks take no more than a couple of hours to fill.
Water Availability	Direct pumping – WTPs must be pumping (on) for end-users to have water filling their tanks.	Standpipe (DUD) or elevated storage tank (Laura) provides sustained pressure, even when pumps are off.
Nonrevenue Water	Leaky asbestos-cement pipes which have served their service life, unknown number of illegal connections.	CIPP seals AC pipe leaky joints or broken pipes – no transmission line leaks, fewer illegal connections.
DUD System Chokepoint	High point in ductile iron pipe at bridge crossing can become "choked" by air bubbles, breaking continuity of flow.	Air/vacuum release valve allows water to flow uninterrupted by air bubbles. System downstream of bridge is not cut off.

psi = pounds per square inch

Pumps run intermittently, depending on water demand and available supply and only to those who have connections. For modeling the Existing Conditions Scenario, we assumed a typical scenario where the current system would run for four hours a day three times a week, and provide 20 gallons per capita per day (gpcd) for residential users, 120 gpcd for Marshall Islands Resort and Hotel Robert Reimers, and 15 gpcd for Majuro High School and College of Marshall Islands. In the Improved Conditions Scenario, we assume that there would be enough water to run the system. With the recommended improvements are constructed, the system would be able to the system provides 40 gpcd for residential users, 150 gpcd for Marshall Islands Resort and Hotel Robert Reimers, and 20 gpcd for Majuro High School and College of Marshall Islands and 40 gpcd for government complex. In addition, it is assumed 100% connections for the system.

6.2. Conceptual Decision Matrix for Recommended System Improvements

Each recommendation to improve the Majuro municipal supply, storage, and distribution system was evaluated at a pre-appraisal, conceptual level, based on professional engineering judgement and experience. The weighting and ranking provided are TSC staff opinions, whereas the final decisions and priorities of these recommendations must be determined by the MWSC and the RMI government. The proposed system improvements are rated on a five-point scale for effectiveness in cost, benefit, urgency, and implementation. A rating of 1 is generally low while a rating of 5 is high. Table 8 shows criteria and weights, and Table 9 provides ranked scores.

Table 8: Ranking Methodology

Category	Low Ranking (1)	High Ranking (5)	Weight
Cost	High cost	Low cost	30%
Benefit	Low benefit	High benefit	35%
Urgency	Low urgency	High urgency	15%
Implementation	Complex implementation	Simple implementation	20%

Table 9: Summary of Scores and Rankings

Improvement	Ranking				Total (Max 500)	Ranking	Notes
	Cost (30%)	Benefit (35%)	Urgency (15%)	Implement-ation (20%)			
Install Flow Control Valves	4	5	5	4	450	1	Benefits all users, would allow system to operate more uniformly and efficiently.
Install Air Valves at the Bridge	5	4	3	5	435	2	Removes trapped air at the system's high point for water flow.
Replace Ductile Iron Pipes at Bridge	5	3	5	5	430	3	Imperative for system reliability and to avoid system outage.
Install a PSV at Laura Pipeline to Airport Reservoir	5	3	3	5	400	4	Maintain a minimum pressure in the Laura pipeline.
Improve Hospital Reverse Osmosis System	3	5	4	3	385	5	Needed to meet regular water demands and future demands projected until 2040.
Provide Rainwater Household Storage Tanks	2	5	4	4	375	6	Address lack of water access at the household level.
Install Public Standpipes	4	2	2	5	320	7	Generate extra revenue for MWSC, minimize illegal connections, and provide access for safe water.
Install a New 400,000-Gallon Standpipe	2	4	3	3	305	8	Would provide more system storage. Flow control valves must be installed first to ensure there is sufficient pressure in the system.
Use CIPP for all Asbestos Cement Pipes	1	5	4	1	285	9	Pipes nearing the end of their design life need to be renewed and this would be safer and less expensive than replacing pipes.
Develop a Rainwater Reservoir at Bokiur Island	3	3	2	2	265	10	Would provide more system storage and serve Ejit residents.
Provide an Elevated Tank for Laura System	4	2	1	3	265	11	Systems with elevated tanks are more expensive to build, they can be less expensive to run.

6.3. Future Work

As part of this work, TSC is delivering an EPANET hydraulic model to MWSC for their reference. A GIS database will also be provided for MWSC’s use as an asset inventory. TSC will train MWSC staff to use and update this GIS database. TSC, and MWSC determined that providing MWSC with WaterGEMS is not cost effective. Therefore, TSC will also present the WaterGEMS model function, capabilities, and current results to MWSC.

6.3.1. Water System Master Planning

Future improvements may include population and water demand projections, storage capacity requirements, fire flow analysis, or "what-if" scenarios. Model scenarios can also be used to analyze and estimate energy cost, water quality, and overall system operation simulations. Reclamation can also assist MWSC with GIS data development. This work will support the MWSC Development Plan.

Upon completion of the model construction and training, additional assistance could be provided by Reclamation to build on the currently outlined work with MWSC. Potential future projects could be assisting MWSC in identifying areas for strategic investment and advising on system improvements based on model scenario analysis. Additionally, the model could be expanded to allow for 2020 to 2040 time-frame master planning and analysis and to consider changing hydrologic impacts, which would assist MWSC in better preparing for future water resources needs and identifying long-term solutions to meet those needs.

6.3.2. Water Supply Analysis

The current modeling work assumes that there is enough water for the improved system. However, as the atoll relies mainly on collecting rainwater, this assumption is not necessarily accurate. TSC would analyze the timing of the water supply and conduct a mass balance evaluation to help formulate a capital improvement program and identify when additional reservoirs would be needed to meet water demands requirement. The mass balance calculations would need to consider expected rainfall, surface water evaporation, and losses during rainwater collection and during treatment.

6.3.3. Leakage Detection and Model Verification

TSC technical experts will assist with the development of a data collection program for the MWSC for leak detection, as current leakage rates from the Asian Development Bank are only an approximation. If the current water distribution system has encountered a leakage of 25% or more, MWSC staff will need to test to generate system pressure data and flow records including pressure recordings of selected locations as well as continuous flow recording of the total flow delivered to the distribution system for at least a 4-hour duration during the low demand (high pressure) period, generally after midnight. Appropriate pressure test site locations have not yet been identified and executed.

6.3.4. Water Treatment Recommendations

The system inherently combines rainwater from private sources and MWSC treated water. Until a reliable water source is provided, this is a secondary problem that may require micro-filtration and treatment on an individual household level. Though important, addressing water quality to meet drinking water standards is a task that will need to be addressed in the future. Significant social preferences for taste (e.g., chlorine) will have to be addressed.

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