TABLE OF CONTENTS

LIST OF FIGURES

POTABLE WATER STUDY

GROUNDWATER MODELING TECHNICAL MEMORANDUM

WASTEWATER ANALYSIS

STORMWATER STUDY

ELECTRICAL SYSTEM ANALYSIS

LIST OF TABLES

POTABLE WATER STUDY

GROUNDWATER MODELING TECHNICAL MEMORANDUM

WASTEWATER ANALYSIS

SOLID AND HAZARDOUS WASTE STUDY

STORMWATER STUDY

POTABLE WATER STUDY

APPENDIX M
UTILITY STUDIES

This page intentionally left blank.

GROUNDWATER MODELING TECHNICAL MEMORANDUM

IN SUPPORT OF THE

COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS JOINT MILITARY TRAINING ENVIRONMENTAL IMPACT STATEMENT

Department of the Navy
Naval Facilities Engineering Systems Command, Pacific
258 Makalapa Drive, Suite 100
JBPHH HI 96860-3134

June 2026

This page is intentionally left blank.

1 INTRODUCTION

1.1 BACKGROUND

The islands of the Commonwealth of the Northern Mariana Islands (CNMI) are strategically located in the United States (U.S.) Department of Defense (DoD) Indo-Pacific area of operations, as shown in Figure 1. Figure 2 shows the Military Lease Area on Tinian where the U.S. military has trained for several decades.

The Proposed Action would support the ongoing and evolving training requirements of U.S. Armed Forces forward deployed to the Western Pacific, and U.S. allies and partners, specifically for distributed operations training within the Military Lease Area on Tinian. Proposed training events would include both ground and aviation training within the Military Lease Area.

Non-live-fire offensive and defensive training actions would continue to be conducted in the Military Lease Area with an increase in existing land-based training events, including both ground and aviation training, which are the same or similar to those currently being conducted on Tinian.

Live-fire training would be conducted at two ranges that would be developed within the Exclusive Military Use Area:

- **Multi-Purpose Maneuver Range.** A live-fire range occupying approximately 200 acres at the northern tip of Tinian to support platoon-size live-fire and maneuver, including three surface radar facilities.
- **Explosives Training Range.** A live-fire range on approximately 2.5 acres for the employment of demolitions and military explosives in support of offensive and defensive training events.

The following are also included in the Proposed Action to support training events:

- Establishment of 13 Landing Zones, areas cleared of vegetation to 6–8 inches, and associated access roads to conduct training events and to provide staging, bivouac, and gathering and rendezvous areas.
- Ground and aviation improvements at North Field, including establishment of a drop zone and the placement of a metal airfield surface.
- Construction and operation of a Base Camp.
- Clearance and improvements of roads within the Military Lease Area.

1.2 PURPOSE

The purpose of this study is to evaluate the potential impact to the groundwater resources on Tinian associated with groundwater extraction to support the proposed CNMI Joint Military Training (CJMT).This study considered groundwater demand, including current and projected demands for all uses (related to the Proposed Action, other DoD, and non-DoD water demands) to evaluate impacts from the Proposed Action. This study supported the determination of impacts associated with the Proposed Action. The Groundwater Modeling Technical Memorandum did not evaluate whether Maui Well No. 2 would be more vulnerable to stresses on the aquifer.

1.3 SCOPE OF STUDY

The goal of this study was to evaluate potential impacts to water quality on Tinian associated with the Proposed Action. The Proposed Action includes the installation of two optional CJMT well fields to provide potable and non-potable water for construction and operation of the proposed Base Camp and CJMT.

The scope of this study is presented below:

- Develop a new groundwater flow model based on the U.S. Geological Survey 2002 model.
- Use available data from Doan et al. 1960, Gingerich and Yeatts (U.S. Geological Survey) 2000, and Gingerich (U.S. Geological Survey) 2002.
- Use data from the CJMT *Aquifer Study Technical Memorandum* (Department of the Navy [DON] 2015).
- Use available head and production data for Maui Well No. 2 provided by the Commonwealth Utilities Corporation.
- Develop model scenarios based on water demands over the course of a typical training year.
- Use the model input sources, calibration, and sensitivity analysis primarily from the U.S. Geological Survey 2002 report. No additional sensitivity analysis will be performed.
- Use model output to evaluate directions of groundwater flow on island.
- Use the model to simulate chloride concentrations under five scenarios.
- Summarize model development, input sources, calibration, sensitivity, model limitations, and modeling results in a *Groundwater Modeling Technical Memorandum*. Include discussion of sea level rise's potential effects on the availability of freshwater via existing and proposed water wells that may assist planners in strategizing future contingency actions.

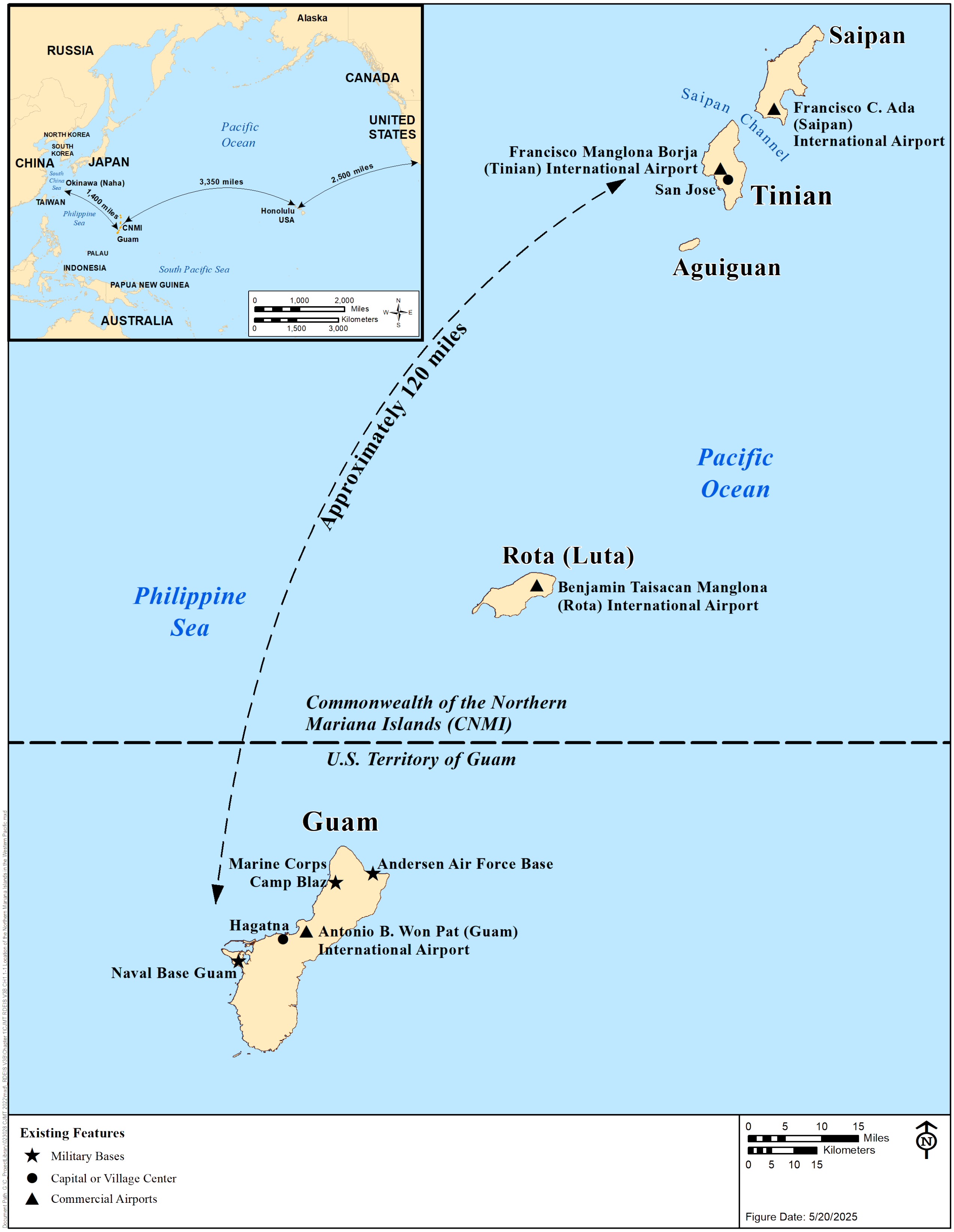


Figure 1 Island of Tinian – Location

Figure 2 Island of Tinian – Military Lease Area Boundaries

2 EXISTING AND PROPOSED WATER SYSTEMS

2.1 EXISTING WELLS

Currently, one potable water well and two groundwater wells are in use on Tinian. The agricultural wells are owned by the CNMI and are provided with electrical power by the Tinian Mayor's Office for the benefit of the cattle ranchers, who can fill potable containers used to provide water to cattle and construction contractors.

2.1.1 Current Potable Supply Wells

The sole supply of potable water on Tinian comes from the Makpo Marsh potential wetland complex's basal groundwater lens. Water is collected from the lens by Maui Well No. 2, discussed below. Tinian's public water system is owned and operated by the Commonwealth Utilities Corporation and serves the southern third of Tinian where the island's entire population resides. The currently operating public system consists of one horizontal Maui well for water supply, three storage tanks, one chlorine injection point, and approximately 38 miles of distribution pipes. A small distribution system serving Francisco Manglona Borja/Tinian International Airport is owned by the Commonwealth Ports Authority. The Commonwealth Ports Authority distribution system consists of a 60,000-gallon (227,100-liter) storage tank and a piping system that receives water from the Commonwealth Utilities Corporation's Maui well subsystem. In the past, additional wells for potable water supply were in operation, but they have since been taken offline and are not maintained in operable condition. Figure 3 shows existing wells on the island.

Maui Well No. 1, also located at the Makpo Marsh potential wetland complex, is currently out of service because the equipment is old and its repair parts have been difficult to obtain. The Maui Well No. 1 pump house was equipped with two 75-horsepower pumps and one 50-horsepower pump, and was originally designed to pump water to the Marpo Heights Tank. Previous plans to refurbish Maui Well No. 1 have been abandoned. Maui Well No. 1 is a Maui-type infiltration gallery constructed in Marpo Marsh within the Median Valley by the U.S. military in 1945. This well is the only well that was not abandoned after World War II; it supplied all of the potable water for Tinian until 1999, when two vertical wells were added to the system. Maui Well No. 1 produced about 1 million gallons per day from the shallow limestone aquifer. The well drew from the upper part of the aquifer over a large area, which tends to maximize the amount of freshwater that can be withdrawn from an area while minimizing upconing of the saltwater.

In 2000–2001, a new 400-foot-long infiltration gallery well (Maui Well No. 2) was constructed near Maui Well No. 1 to replace that well. According to the *2012 Water Quality Report* (Commonwealth Utilities Corporation 2013), Maui Well No. 2 supplied all Commonwealth Utilities Corporation water in 2012. Maui Well No. 2 has four 75-hp pumps, each capable of pumping about 350 gallons per minute for a total of 1,400 gallons per minute to both the Marpo Heights and Carolinas Tanks as well as the Commonwealth Port Authority Airport Tank. Currently, Maui Well No. 2 supplies the Commonwealth Utilities Corporation's entire Tinian water system, operating three of its four pumps almost constantly (Commonwealth Utilities Corporation 2013). Because one pump is kept on standby for maintenance purposes, Maui Well

No. 2 operates at near-full capacity. Additional information on Tinian's potable water system is provided in the *Potable Water Study* (DON 2025).

At various times, other vertical wells (e.g., TH-06 [capable of 60 gallons per minutes] and TH-04 [capable of 50 gallons per minute]) have been in use by the Commonwealth Utilities Corporation. Additional details, including ownership of the individual wells, are included in Attachment A – Known Current and Former Wells.

2.1.2 Existing Non-potable Supply Wells

Well M-21 was previously used by cattle ranchers. Currently, it is used primarily by the construction contractor for the U.S. Air Force Tinian Divert Activities and Exercises (Divert) Infrastructure Improvements at the Francisco Manglona Borja/Tinian International Airport. This well was permitted in 2024 to extract not more than 1.8 million gallons per month (DON 2025).

Well M-26 is primarily used by cattle ranchers and is not metered. Well M-26 agricultural water demand has been estimated at 59,178 gallons per day.

These wells are labeled M-21 and M-26 in Figure 3. Except for these two, no other wells within the Military Lease Area (the northern roughly two-thirds of the island) are known to be in use. During the aquifer study, M-21 and M-26 were used to produce about 25 gallons per minute each to cattle ranchers.

2.1.3 Existing Monitoring Wells

Some of the historical literature suggests that the Japanese military may have dug more than 100 wells during their occupation of Tinian. Most of these were reportedly filled in. The U.S. military constructed approximately 40 (M-series) groundwater wells in 1944 and 1945 on the island for water supply, including Maui Well No. 1. Most of these were reportedly drilled to 10 or 15 feet below mean sea level. The majority of the M-series wells have been inactive since shortly after World War II (Doan et al. 1960).

Between 1993 and 1997, the U.S. Geological Survey rehabilitated 16 of the inactive U.S. military wells. Rehabilitation involved retrieving the original pump and pipe, re-drilling as necessary, cleaning out the hole to near the original depth, and installing new surface casing/well head features, if necessary. In addition, between 1993 and 1997, U.S. Geological Survey drilled 17 new (TH-series) wells for groundwater monitoring in the Median Valley and the adjacent Southeast Ridge and Central Plateau. Of the 17 wells, 12 are open holes and 5 are cased with polyvinyl chloride pipe and screened below the water table. All wells were drilled into the top of the freshwater lens except wells TH-02, TH-04X, TH-08, and TH-09, which were drilled into the transition zone. The freshwater lens thickness and underlying transition zone fluctuate as a result of seasonal rainfall and groundwater withdrawal (U.S. Geological Survey 2000). At least one of the M-series wells (M-29) was deepened through the transition zone (to a depth of 168 feet below mean sea level) and used as a transition zone monitoring well for a period of time. However, no records of this transition zone monitoring have been located despite searches by U.S. Geological Survey staff.

Figure 3 Tinian Existing Wells

In 2012, a hydrogeologic assessment of groundwater conditions was completed at the planned Tinian landfill site and surrounding area (Tetra Tech 2012). The Tinian landfill site was a proposed municipal solid waste landfill northwest of the airport. The scope of work for the assessment included installation of three monitoring wells: WOP-197-01, WOP-197-02, and WOP-197-03. Although the basis for the well nomenclature used by the Bureau of Environmental and Coastal Quality is unknown, it is understood that these three refer to monitoring wells at the proposed landfill.

2.1.4 CJMT Proposed Action Water Wells

Potable and non-potable water for the Proposed Action are expected to come from four new wells located in Well Field A or B located northeast or northwest of the Tinian International Airport, respectively (Figure 4). Groundwater elevations in the area are generally less than 1 to about 2 feet above msl in the notional DoD well field.

Other On-island Wells

Following construction for U.S. Air Force’s Tinian Divert Infrastructure Improvements at the Francisco Manglona Borja/Tinian International Airport, U.S. Air Force would use a newly installed firefighting well. The average demand for this well is estimated at 2,192 gpd.

U.S. Air Force plans to rehabilitate an existing well (assumed to be existing well M-05) for construction at North Field. The average demand for this well is estimated at 12,000 gallons per day.

¹This is an approximate location.
*For smaller features a symbol was used and is being shown but not to scale.
**Additional water service lines would be connected into the chosen Base Camp option.
***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure 4 Tinian Future Wells

3 WATER DEMANDS FOR PROPOSED ACTION

The Proposed Action includes construction of new water infrastructure to fully support the U.S. Marine Corps' (USMC) proposed CJMT and to avoid impacts on the Commonwealth Utilities Corporation water system. This proposed new water infrastructure would supply the domestic, industrial, and fire protection demands of military training activities and the majority of water used during construction. This proposed new water infrastructure would be operated by the DoD and would not be connected to the Commonwealth Utilities Corporation water system.

Domestic demand on the Commonwealth Utilities Corporation water system would also increase because of the Proposed Action. Operations staff and construction workers would live outside the Military Lease Area or stay in hotels and become customers of the Commonwealth Utilities Corporation water system.

These future demands are summarized in Table 1.

Table 1. Summary of Average Future Annual Water Demands on Tinian

Owner	*Facility*	*Type*	*Average Annual Water Demand (gallons per year)*	*No. Wells*
Military	CJMT Base Camp [a]	Potable	7,971,440	4
Military	CJMT North Field	Non-Potable	800,000	2
Military	USAF North Field Rehabilitation	Non-Potable	4,380,000	1
Military	Tinian Divert Infrastructure Improvements	Potable	800,000	1
CUC	Maui Well No. 2 [b]	Potable	314,727,702	1
Tinian Mayor's Office	Well M-21 (CJMT Construction)	Non-Potable	21,600,000	1
Tinian Mayor's Office	Well M-26 (Existing Agriculture)	Non-Potable	21,600,000	1

Notes: [a] Total demand for all the wells.
[b] Average of production at Maui Well No. 2 from 2019 to 2023 and proposed CJMT demands on the CUC water system.

Legend: CJMT = Commonwealth of the Northern Mariana Islands Joint Military Training; CUC = Commonwealth Utilities Corporation; gpd = gallon per day; U.S. = United States; USAF = United States Air Force.

Source: *Potable Water Study Update* (DON 2025).

4 GROUNDWATER AND GEOLOGY

4.1 GROUNDWATER SUPPLY

Rainfall is the primary source of fresh groundwater on Tinian. The U.S. Geological Survey estimates the average annual groundwater recharge for Tinian to be approximately 30 inches per year (U.S. Geological Survey 2002). This translates into approximately 62,000 acre-feet per year of recharge. The rapid downward percolation of rainwater into porous limestone rock (Doan et al. 1960) recharges Tinian's basal freshwater aquifer. Fresh groundwater on Tinian is primarily classified as basal, which is a body of fresh groundwater that floats on saline groundwater. The portion of the basal freshwater lens that is usable for potable water, which has chloride concentrations less than 250 milligrams per liter, is thickest south and southwest of Mount Lasso and becomes increasingly thinner approaching the coastline. The groundwater table on Tinian ranges from sea level around the perimeter of the island to over 3 feet above msl in the central portions of the island. Groundwater flows outward from the North Central Highland and the southeastern ridge, and generally seaward around the island (DON 2015). Most of the fresh groundwater slowly discharges naturally from springs around the perimeter of the island and submarine coastal springs. The basal freshwater lens underlying Tinian is the principal source of drinking water and meets the definition of an aquifer found in CNMI Title 65, Chapter 65-90-010, and U.S. Environmental Protection Agency (EPA) regulations.

4.1.1 Physical Environment of Tinian

Physical features relevant to the groundwater modeling include topography, climate, geology, hydrogeology, and the existing well network and water supply systems. These features are detailed in the *Aquifer Study Technical Memorandum* (DON 2015).

4.1.2 Topography

Tinian is about 12 miles long and 6 miles wide. It is separated from Saipan by the approximately 3-mile-wide Tinian Channel. Tinian comprises a series of limestone plateaus separated by steep slopes and cliffs (U.S. Department of Agriculture Soil Conservation Service 1989). The surface landforms (Figure 5) are divided into five major physiographic areas based on topography and spatial relations, as described below (U.S. Geological Survey 1999). These are depicted along with representative spot elevation in Figure 5:

- **Southeastern Ridge.** This land area is the southernmost and highest part of the island, with a maximum elevation of 614 feet at Mount Kastiyu. Steep slopes and cliffs up to 500 feet in height on the southeast characterize this area.
- **Median or Marpo or Makpo Valley.** This land area is a low, broad, elongated depression northwest of the Southeastern Ridge with a maximum elevation of 150 feet. In the valley, the land surface intersects the water table, resulting in a small potential wetland complex known as the Makpo Wetland or Makpo Marsh.
- **Central Plateau.** This land area extends northward from the Makpo Valley and includes central Tinian and portions of northern Tinian. The plateau is broad and gently sloping, with most of the vertical relief at its southern and northern boundaries.

- **North-Central Highland.** This land area is located within the northern part of the Central Plateau and midway between the east and west coasts of the island. The maximum elevation of the highland at Mount Lasso is 545 feet.
- **North Lowland.** This land area is located at the northern tip of Tinian. It is generally flat with an average elevation of approximately 100 feet, except for the Lake Hagoi wetland, where the land elevation is approximately at sea level.

4.1.3 Climate

The seasons on Tinian are defined by distinct differences in rainfall. During the wet season, which occurs between the months of July and October, the island receives roughly 60 percent of its annual precipitation. February through May comprise the dry season, when only about 10 percent of Tinian's annual rainfall occurs. The remaining months (November, December, January, and June) are the transitional months when the island receives the remaining 30 percent of its rainfall. Rainfall from tropical storms and typhoons, in years when they occur, can comprise a significant percentage of the total annual rainfall, and a lack of storms can significantly contribute to drought conditions. Typical temperatures range from 76 degrees Fahrenheit to 88 degrees Fahrenheit (U.S. Geological Survey 2002).

Precipitation averaged about 81 inches per year at the airport weather station from 1988 to 1994 and in 1996, years for which complete daily rainfall records were available. Because the highest point on Tinian is only 614 feet above mean sea level, orographic effects (increased rainfall related to mountain ranges) appear to be minimal. Gingerich and Yeatts measured rainfall at four sites on Tinian from 1993 to 1996, and the measured amounts ranged from 72 to 82 inches across the island (U.S. Geological Survey 2000). Gingerich used an average rainfall of 82 inches per year in the water budget for the numerical groundwater flow model (U.S. Geological Survey 2002).

Figure 5 Tinian Physiographic Areas

4.1.4 Geology

Tinian is a composite carbonate island (Jenson et al. 2006) consisting of geologically young coralline and algal limestone strata overlying an older core of volcanic tuff and breccias, small portions of which crop out at the surface in two small places on the island (Figure 6). The limestone retains substantial primary porosity but also exhibits regional- to local-scale fractures (secondary porosity) associated with regional tectonic stresses and local loading/unloading from uplift-subsidence and deposition-erosion cycles. Regional high-angle normal faults result in offset limestone plateaus that characterize the island (Figure 6). Figure 7 shows geologic cross sections of Tinian.

Tinian comprises the following four major geologic units, shown in Figure 6 (U.S. Geological Survey 2002):

- **Tinian Pyroclastic Rocks.** Tinian Pyroclastic rocks are the oldest rocks exposed on the island (Late Eocene age; about 38 million years old), which likely underlie all other exposed rock units there. These fine- to coarse-grained ash and angular fragments represent explosive volcanic materials ejected from an ancient volcano that formed the core of the island. These rocks are exposed on the North-Central Highland and Southeastern Ridge where they occupy about 2 percent of the surface of Tinian today. Surface exposures are generally highly weathered and typically altered to clay minerals.
- **Tagpochau Limestone.** Of Early Miocene age (approximately 23–20 million years old), Tagpochau Limestone rocks are exposed on about 15 percent of Tinian’s surface, generally in the North-Central Highland and the southern part of the Southeastern Ridge. These rocks range up to about 600 feet in thickness. They are composed of fine- to coarse-grained, partially recrystallized broken limestone fragments, and about 5 percent reworked volcanic fragments and clays. Surface exposures are highly weathered, and this unit extends from the unconformity with the volcanic rocks below to the ground surface in the North-Central Highland and the southern part of the Southeastern Ridge, mentioned above. Across most of the island, this unit is capped by the Mariana Limestone.
- **Mariana Limestone.** These Pliocene to Pleistocene age (about 5–3 million years old), Mariana Limestone rocks cover approximately 80 percent of Tinian’s surface, forming nearly all of the North Lowland, the Central Plateau, and the Makpo Valley. These rocks range up to about 450 feet in thickness. They are composed of fine- to coarse-grained fragmented limestone, with some fossil and algal remains, and small amounts of clay particles. Small voids and caverns (tertiary porosity) are common in surface exposures. Overall, the Mariana Limestone has a higher coral content than the Tagpochau Limestone.
- **Beach Deposits, Alluvium, and Colluvium.** Shallow Pleistocene to Holocene age (approximately 2 million years old to the present) sediments mantle less than 1 percent of Tinian’s surface and range up to approximately 15 feet thick. The deposits consist of poorly consolidated sediments, which are mostly calcareous sand and gravel deposited by waves. However, they also contain clays and silts deposited inland surrounding Lake Hagoi and the Makpo Marsh potential wetland complex. Loose soil and rock material (talus) are found at the base of slopes.

*For smaller features a symbol was used and is being shown but not to scale.

Data Sources: Gingerich and Yeatts 2000 (Modified from Doan and others 1960)

Figure Date: 5/20/2025

Figure 6 Tinian Generalized Surficial Geology

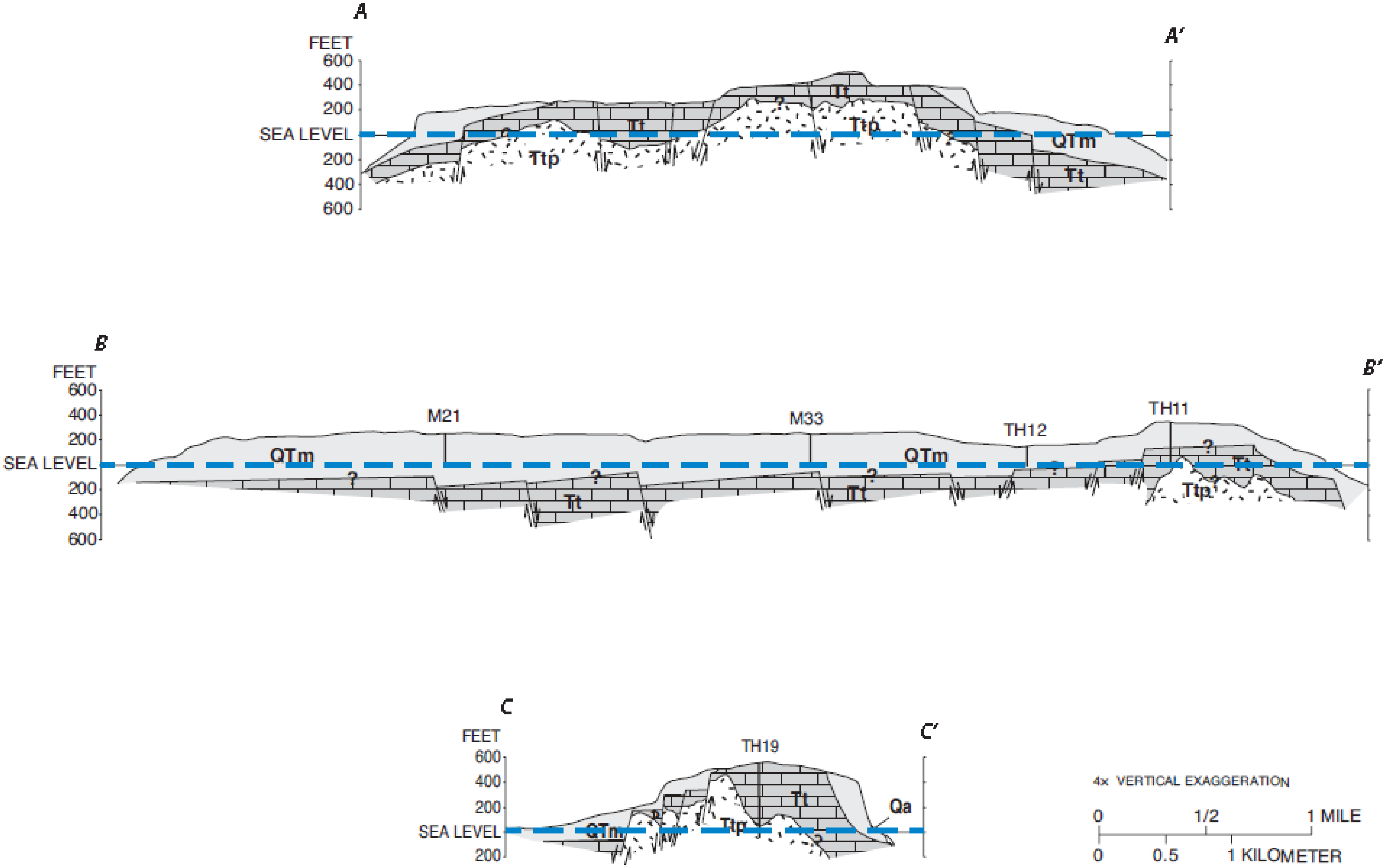


Figure 7 Tinian Geologic Cross Sections

Source: U.S. Geological Survey 2000 (after Doan et al. 1960).

4.2 GROUNDWATER RESOURCES OF TINIAN

4.2.1 Overview

Groundwater is recharged by rainfall infiltration over most of Tinian. Water that recharges the groundwater system flows from zones of higher to lower hydraulic head. Ideally, fresh groundwater (chloride less than 250 milligrams per liter) forms a double-convex lens in a cross section and is underlain by denser saltwater (chloride concentration of 19,000 to 20,000 milligrams per liter); however, the base is distorted where it contacts the relatively impermeable volcanic basement rock. The Ghyben-Herzberg relationship (Baydon-Ghyben 1888–1889, Herzberg 1901) is commonly used to relate the thickness of a freshwater lens in an ocean-island aquifer to the density difference between freshwater and saltwater. A generalized cross section of the freshwater lens is presented in Figure 8. Doan et al. (1960) reports the existence of such a basal freshwater lens in areas near the north end and center portion of the island. The theoretical interface between freshwater and saltwater will be at a depth below sea level about 40 times the height of the water table above sea level. Instead of a sharp freshwater/saltwater interface, however, freshwater is separated from saltwater by a transition zone in which salinity grades from freshwater to saltwater. In many field studies, the theoretical Ghyben-Herzberg interface depth within the transition zone is generally defined as the depth of about a 50 percent mix of freshwater and saltwater (i.e., roughly equal to a chloride concentration of 9,500 to 10,000 milligrams per liter). Under equilibrium flow conditions in permeable aquifer systems, the Ghyben-Herzberg relationship may provide a reasonable estimate of freshwater depth if the transition zone is comparatively thin (U.S. Geological Survey 2002). Pumping freshwater tends to disturb this equilibrium, resulting in a thinner freshwater lens and thicker transition zone. Freshwater lens thickness is affected by aquifer permeability and recharge rates. A reduction in recharge rate or an increase in permeability will reduce the thickness of the freshwater lens.

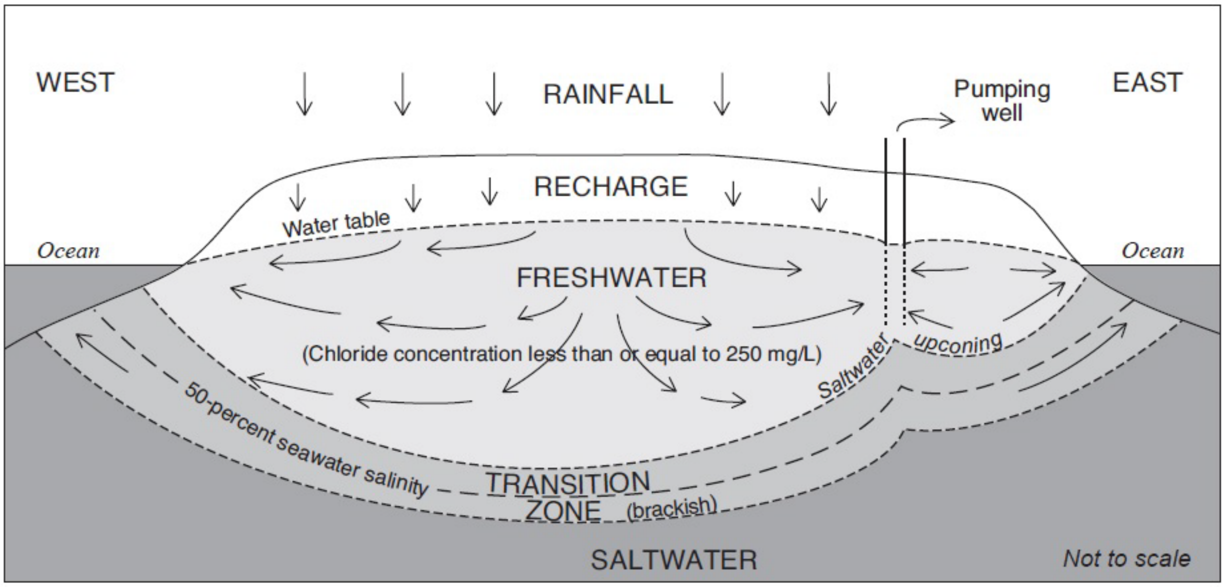


Figure 8 Generalized Depiction of a Freshwater Lens above Saltwater

Source: U.S. Geological Survey 2000.

In very permeable limestone, the water table is no more than a few feet above sea level, and the slope of the water table is nearly flat (U.S. Geological Survey 2002). Based on the Ghyben-Herzberg Principle, the depth to the 50% isochlor on Tinian should vary from a maximum of about 80 feet below mean sea level around the Central Plateau where the groundwater stands about 2 feet above mean sea level, decreasing radially to sea level around the perimeter of the island.

Potable and non-potable water for the proposed action is expected to come from one of two new well fields (Well Fields A and B, shown in Figure 4).

The groundwater surface has been mapped (Doan et al. 1960; USGS 2000) in the notional DoD well field to range from about 0.8 to 1.6 feet above mean sea level. Assuming an ideal freshwater lens, the 50 percent isochlor would vary from about 32 to 64 feet below mean sea level in the center of the island and would thin toward the coast. The portion of the lens that is useful for potable water (i.e., with a chloride concentration of less than 250 milligrams per liter [approximately 1 percent isochlor]) is likely thinner than the theoretical 50 percent isochlor depth.

Most of the fresh groundwater discharges naturally from the aquifer at onshore and submarine coastal springs. Stafford et al. (2004, 2005) documented caves, fractures, and coastal springs on Tinian, which can be locally important for groundwater development. A small amount of groundwater may be lost locally to evaporation and transpiration at the Makpo Marsh potential wetland complex and Hagoi Lake (U.S. Geological Survey 2002).

4.2.2 Hydrogeology

Hydraulic conductivity is a quantitative measure of the capacity of a rock to transmit water. Limestone units tend to have high hydraulic conductivities because of the porous and well-washed character of coral reefs, as well as secondary porosity as a result of dissolution. In contrast, pyroclastic rocks tend to have much lower hydraulic conductivities as a result of poor sorting and the high susceptibility of some volcanic minerals to chemical weathering and alteration to clays (U.S. Geological Survey 2002), as is the case on Tinian.

Tinian, a composite karst island aquifer (Jenson et al. 2006), is a triple-porosity aquifer. The young limestone retains substantial primary (interparticle or matrix) porosity, which makes the dominant contribution to storage and usually local transmission to wells. Regional transmissivity is dominated by widened fractures, which may develop along faults or along tension fractures. Where wells intercept the fracture network, performance can be one or more orders of magnitude higher than for wells that draw their production exclusively from local matrix porosity. The third source of porosity in composite islands is conduits (cave systems) that can develop along the contact between the overlying soluble limestone aquifer and the underlying insoluble volcanic basement. Such conduits can develop along the flanks of the basement rises and ridges where they stand above sea level or have been above sea level during ice-age, sea-level low-stands (Vann et al. 2013). Hydraulic conductivities in carbonate island karst aquifers can range from local values of 1 to 10^3 feet per day to regional values of 10^3 to 10^4 feet per day (Rotzoll et al. 2013).

The Tinian pyroclastic rocks are generally believed to have much lower permeability than limestone because of their texture and density and are essentially considered non–water-bearing for the purposes of this study. The overlying Tagpochau Limestone, where it exists beneath current ocean levels, and the Mariana Limestone that overlies it are both considered viable aquifers in this study. The minor beach deposits, alluvium, and colluvium are not situated in areas or at elevations that make them viable as groundwater resources for the purposes of this study. Doan et al. (1960) reported historical well productions from the military wells ranging from nil to 100 gallons per minute, with the majority being in the 60 to 100 gallons per minute range. The U.S. Geological Survey performed aquifer tests on Tinian between 1994 and 2000 to estimate the hydraulic conductivity of the Tinian aquifers (Tagpochau Limestone and Mariana Limestone). Pumping rates for the tests ranged from 3 to 165 gallons per minute. Resulting estimates of hydraulic conductivity in Tagpochau Limestone and Mariana Limestone on Tinian ranged from 21 to 23,000 feet per day.

The U.S. Geological Survey prepared a groundwater model in *Geohydrology and Numerical Simulation of Alternative Pumping Distributions and the Effects of Drought on the Ground-Water Flow System of Tinian, Commonwealth of the Northern Mariana Islands* (U.S. Geological Survey 2002). For modeling purposes, Tinian was divided into three horizontal hydraulic conductivity zones: (1) highly permeable limestone, (2) less permeable, clay-rich limestone, and (3) lowpermeability- volcanic rocks. The two-dimensional, steady-state groundwater flow model was developed to enhance the understanding of: (1) the distribution of aquifer hydraulic properties, (2) the conceptual framework of the groundwater flow system, and (3) the potential effects of various pumping distributions and drought on water levels and the freshwater/saltwater zones. For the modeling, the U.S. Geological Survey used values of 10,500 feet per day for highly permeable limestone, 800 feet per day for less permeable limestone, and 0.2 feet per day for volcanic rock (U.S. Geological Survey 2002). This 4 to 5 order-of-magnitude contrast is not unusual in composite islands. The U.S. Geological Survey monitored and contoured ambient groundwater elevations for further understanding of the groundwater flow regime (U.S. Geological Survey 2000). Groundwater generally flows radially away from the North Central- Highland and the Southeastern Ridge.

4.3 WATER QUALITY

Chloride concentration is an important secondary standard for Maui Well No. 2 because it has the potential to indicate the quantity of freshwater available at that location. The secondary maximum contaminant level for chloride is 250 milligrams per liter. Table 2 provides chloride concentrations at Maui Well No. 2 between 2012 and 2023.

Table 2. Chloride Concentrations at Maui Well No. 2

Year	*Chloride (mg/L)*	
	Average	*Range*
2012	196	175–223
2013	190	172–217
2014	213	212–214
2015	213	212–214
2016	190	184–196
2017	184	184
2018	176	176
2019	146	NA
2020	145 [a]	NA
2021	176 [a]	158–176
2022	176 [a]	158–176
2023	177	NA

Notes: [a]Value revised to highest instead of average.
Legend: mg/L = milligrams per liter; NA = not available; No. = Number.
Source: Commonwealth Utilities Corporation 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024.

U.S. Geological Survey 2002 reported that chloride concentration at the Municipal well [Maui Well No. 1] did not change significantly during 1992–1997, averaging about 180 milligrams per liter, and ranging from 160 to 220 milligrams per liter. The average chloride concentration is about 100 milligrams per liter higher than initially measured during non-pumping conditions after construction in 1945 (Lawlor 1946), and 100 milligrams per liter higher than at other wells in the median valley.

Salinity in a freshwater lens is gradational, consisting of an upper freshwater core through an underlying transition zone to saltwater below. However, depending on aquifer permeability and the strength of tidal influence, the transition from freshwater to saltwater can be gradual or sharp. On small islands, mixing in the transition zone results mainly from tidal fluctuations superimposed on the gravity-driven flow of freshwater toward the shore. In areas near the coast where mixing is thorough, a freshwater lens may not form and brackish water may exist even at the water table. Under conditions of steady recharge, no pumping, and no ocean-level effects, the steady-state lens would have fixed dimensions. In reality, rainfall is episodic and seasonal, and lens volume fluctuates naturally with time. Tidal fluctuations, variable recharge, and episodic pumping all combine to create a thicker transition zone than would be present without these influences (U.S. Geological Survey 2002). Figure 8 shows a generalized graphic depiction of a freshwater lens above a saltwater wedge on a small island.

Based on monitoring performed by the U.S. Geological Survey in the 1990s, the transition zones in wells TH-08 and TH-09 (monitoring wells installed by the U.S. Geological Survey in 1993) varied from approximately 30 to 50 feet thick in 1993 and 1994. Doan et al. (1960) report 20 pre-pumping chloride concentration results ranging from 16 milligrams per liter to 650 milligrams per liter. Two of the samples exceeded the EPA’s secondary maximum concentration level for chloride of 250 milligrams per liter. Ten pairs of pre-pumping and post-pumping chloride concentration results are also reported (U.S. Geological Survey 2000). Prior to pumping, 1 of the 20 wells (with pre- and post-pumping data) exceeded the secondary maximum concentration level and, after pumping, 2 to 3 wells exceeded that standard. One of the post-pumping results was simply recorded as “high,” but it is assumed this refers to a concentration higher than 250 milligrams per liter. Seven to 8 of 10 wells remained below the secondary maximum concentration level at the end of pumping. The U.S. Air Force commissioned testing of two wells in the North Field area in November 2025. Based on that testing, chloride concentrations at the Ushi and M-10 wells were reported to range between 2,254 to 2,499 mg/L, and 2,058 and 2,499 mg/L, respectively during 36-hour constant rate testing (APEC 2025). Note that these values are an order magnitude higher than the value of 220 mg/L reported by Doan et al 1960 for the Ushi Well measured at the end of pumping (date of measurement is unknown). No values were reported at M-10 or at the beginning of pumping at the Ushi Well. It is possible that the values obtained in November 2025 were influenced by drier-than-normal conditions reported at that time. According to drought.gov “In the Commonwealth of the Northern Mariana Islands (CNMI), southern FSM (Kapingamarangi), and western RMI (Kwajalein), drier-than-normal conditions prevailed during SON” [September to November 2025] (NOAA, 2025). The site describes La Niña conditions with below-normal sea surface temperatures across the central and eastern equatorial Pacific Ocean during that period of time.

Bureau of Environmental and Coastal Quality provided the following information in Captain Brian Bearden’s email to Jacqueline Rice from Headquarters, USMC, forwarded to Doug Gilkey on March 3, 2025:

> [Bureau of Environmental and Coastal Quality]’s previous review comments raised a number of concerns with the proposed location near the airport, primarily related to the potential to contaminate valuable groundwater resources. That location was within an area where we have documentation and other data that would support classification as a Class I Aquifer Recharge Area/Groundwater Protection Zone as established or references [sic] in several CNMI regulations. Our primary documentation supporting this concern is the 2000 USGS Water investigations Report 00-4068 which shows the area on the north side of the airport as being within the boundaries of the +1.0 feet groundwater elevation contour, which the CNMI Well Drilling and Well operations regulations (NMIAC [Northern Mariana Islands Administrative Code] § [Section] 65-140-2010) utilize as the boundary of the Class II groundwater protection zones, which also contains the Class I zones which are more loosely defined to include “municipal wellfields” and other resources that are either currently in use for water supply, or meet specific other criteria.
>
> In contrast to this, the IBB [International Broadcasting Bureau] site is in an area that appears to not be within either a Class I or II Aquifer Recharge Area/Groundwater Protection Zone. Even though the USGS report does not show groundwater elevation contours in this particular area due to lack of data, the map contours can be reasonably extrapolated, supported by general knowledge of island freshwater lens hydrology, to strongly suggest that the IBB site is located outside the potential boundaries of any future Class I or II groundwater protection zone designation. Thus, the IBB site would not trigger the same level of concern stated in [the Bureau of Environmental and Coastal Quality]’s previous comments related

to the locations closer to the airport and would be a preferred location to minimize such concerns.

Table 3 summarizes water production (i.e., extraction) quantities from Maui Well No. 2 as recorded by the Commonwealth Utilities Corporation at the well site. Production includes water delivered into the distribution system, which is inclusive of water billed to customers, unmetered uses, leaks, losses, and overflows.

Table 3. Commonwealth Utilities Corporation Water Production from Maui Well No. 2

Year	*Total Annual (MG)*	*Average Daily (MGD)*
2019	313	0.86
2020	312	0.85
2021	307	0.84
2022	321	0.88
2023	306	0.84
2019 to 2023 Average	NA	0.85

Legend: CUC = Commonwealth Utilities Corporation; MG = million gallons; MGD = million gallons per day; NA = not applicable; No. = number.
Source: Commonwealth Utilities Corporation 2024a.

5 MODELING

5.1 MODELING APPROACH

The U.S. Geological Survey developed a groundwater flow model to simulate groundwater conditions on the island, with the results published in a 2002 report. The model was constructed using the quasi-three-dimensional SHARP computer program developed by H. I. Essaid for the U.S. Geological Survey (Essaid 1990). SHARP is a finite difference code that models both fresh and saltwater flow and approximates a sharp interface between the two solutions. In the model, each of the limestone and volcanic rock aquifers is represented by a single model layer, and flow within the layer is assumed to be horizontal.

The 2002 SHARP model has several limitations. It assumes that freshwater and saltwater do not mix, preventing it from predicting salinity distribution within the aquifer or the quality of water pumped from a specific well. While the model can simulate the location of the freshwater/saltwater interface, it cannot accurately predict local drawdown or rise in the interface beneath a pumped well. Additionally, since the groundwater flow model consists of only two relatively thick layers, it lacks the resolution needed to simulate vertical head gradients effectively.

5.1.1 Previous Modeling Effort

The U.S. Geological Survey developed a groundwater flow model to simulate groundwater conditions on the island, with the results published in a 2002 report. The model was constructed using the quasi-3-D SHARP computer program developed by H. I. Essaid for the U.S. Geological Survey (Essaid 1990). SHARP is a finite difference code that models both fresh and saltwater flow and approximates a sharp interface between the two solutions. Each aquifer in the model is represented by a single layer, and flow within the layer is assumed to be horizontal.

5.1.2 Model Selection

Many numerical modeling codes are capable of simulating variable density conditions, and the modeling process is typically approached in a phased manner. Several American Society for Testing and Materials International standards exist to guide the modeling process. American Society for Testing and Materials D6170-17 (2010b) and American Society for Testing and Materials D5447-04 (2010a) contain recommendations for selecting a groundwater modeling code and applying that code to a site-specific problem.

The computer code selected to model groundwater flow was the Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW) 2000, a 3-D, cell-centered, finite difference, saturated-flow model developed by the U.S. Geological Survey (originally developed by McDonald and Harbaugh 1988). The Groundwater Modeling System (GMS) provides an interface to the updated version of MODFLOW 2000 (Hill et al. 2000). Based on the information available, the uncertainty associated with site information, and the modeling objective, MODFLOW 2000 was considered an appropriate groundwater flow code.

Chloride transport simulations were conducted using the Modular Three-Dimensional Multispecies Transport Model for Simulation (MT3DMS) groundwater contaminant transport model code (Zheng and Wang 1999). MT3DMS is an improved version of the MT3D model developed in 1990 (Zheng 1990). This model has improved numerical solvers that make it more stable and prevent model-induced numerical oscillations. GMS provides a module that links MODFLOW groundwater flow information to MT3DMS. MT3DMS uses this information to simulate contaminant transport using the MODFLOW -simulated groundwater flow field.

SEAWAT (Version 4, U.S. Geological Survey 2008) was developed to simulate variable density flow resulting from high concentrations of solutes, typically salt. SEAWAT was built on the MT3DMS platform and solves iteratively for flow, transport, and the resulting density variations that impact flow.

The groundwater model software package selected for this effort was GMS (Version 10.8, Aquaveo 2021). GMS is a comprehensive graphical-user interface for performing groundwater simulations and provides various powerful tools for data interpolation and figure generation. The entire GMS consists of a graphical user interface (the GMS program) and a number of analysis codes (e.g., MODFLOW, MODPATH, MT3DMS, RT3D, SEAWAT). GMS was developed by the Environmental Modeling and Research Laboratory in partnership with Waterways Experiment Station and was used as a supplementary tool to assist with preparing and interpolating data, pre- and post-processing, and generating figures (Environmental Modeling and Research Laboratory 2005).

5.1.3 Model Construction

A model grid was created with a domain extent matching that outlined in the 2002 U.S. Geological Survey model document. The original SHARP input files were obtained from the U.S. Geological Survey, and the model layer elevations and properties were extracted for import into the new MODFLOW grid. Although the 2002 U.S. Geological Survey model files provided limited data on aquifer geometry and properties, the model results are deemed reasonable for the intended purposes.

5.2 MODEL DESIGN

The lateral extent of the modeled area is shown in Figure 9. The domain includes the entire island of Tinian, an area offshore extensive enough to minimize boundary interferences with simulated groundwater flow on the island, and the offshore area where fresh groundwater discharges to the ocean (U.S. Geological Survey 2002).

5.2.1 Grid and Layering

The model grid (Figure 9) is non-uniform, composed of 81 rows and 73 columns, and covers an area of approximately 58,400 feet east to west and 92,520 feet north to south. The total modeled area encompasses approximately 194 square miles). Maximum cell dimensions are approximately 2,336 feet by 3,700 feet, and the minimum cell size is 925 feet by 584 feet (localized to the island).

Data Sources: Gingerich and Yeatts, USGS 2000, CNMI DEQ 2014
*For smaller features a symbol was used and is being shown but not to scale.

Figure Date: 5/20/2025

Figure 9 Groundwater Model Domain

The initial U.S. Geological Survey model consisted of two layers that were later subdivided into eight model layers. Layers 1 through 3 represent the karst aquifer materials and some shallower volcanic rocks, while layers 4 through 8 only include volcanic basement material. The original and subdivided model cross sections are shown in Figure 10. To avoid dry cells, the bottom of model layer 1 was set to -15 feet mean sea level across the island, which matches the screen bottom elevation of the proposed four new CJMT water wells. However, in the area near Maui Well No. 2, the bottom of layer 1 was locally set to -2 feet mean sea level to align with the bottom screen elevation of Maui Well No. 2.

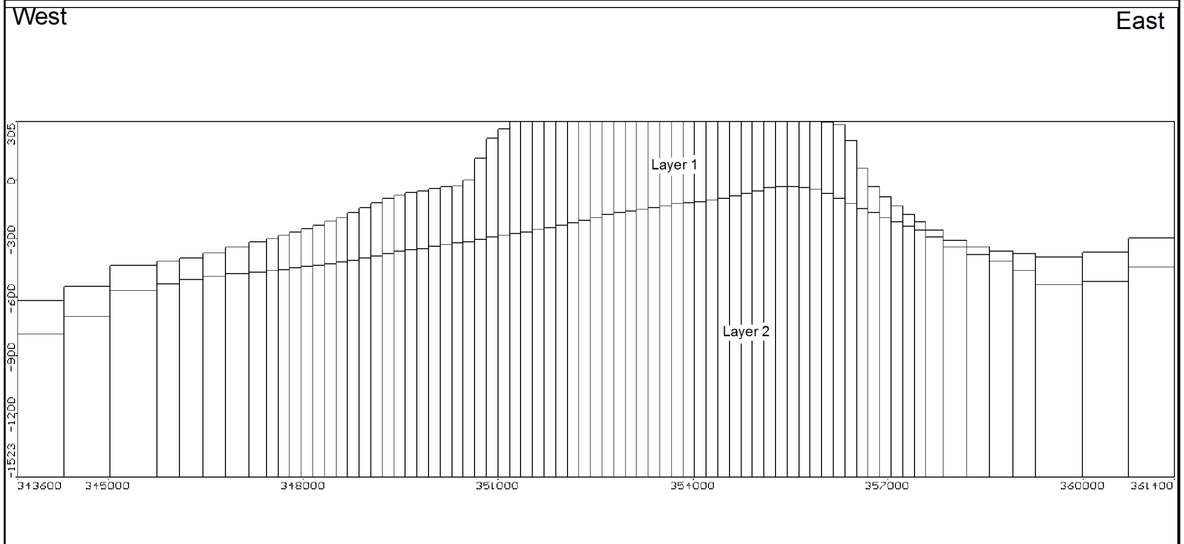
5.2.2 Boundary Conditions

Because the 2002 U.S. Geological Survey model layer 1 was divided into three model layers in the new model development, the ocean in model layer 1 was simply represented using a constant-head boundary. In model layers 2 through 8, the four edges of model were also applied to a constant-head boundary (Figure 11).

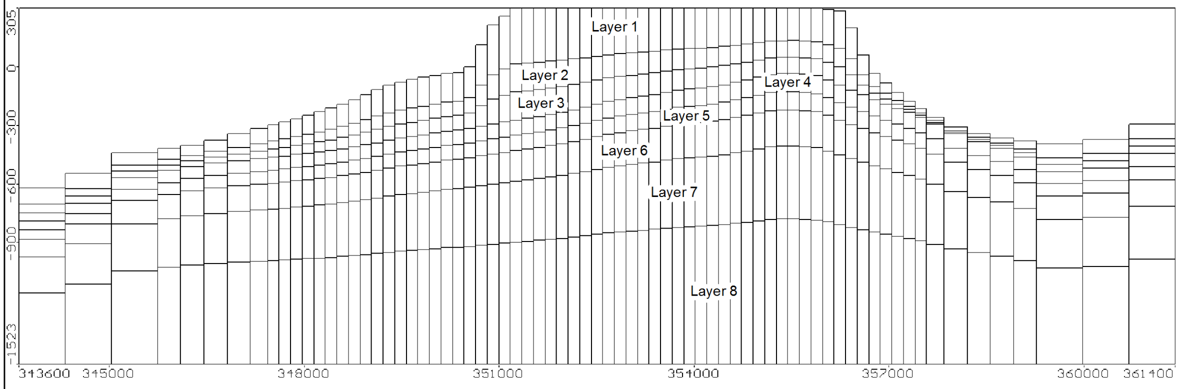
In the 2002 model, recharge was applied to layer 1 of the model over the island at a uniform rate of 29.7 inches per year. In the AECOM 2025 model, recharge was distributed spatially over the limestone areas, with low-permeability rock areas receiving a minimal recharge rate. This is discussed further in Section 5.3 of this report.

To account for the background chloride component, a concentration of 30 milligrams per liter was assigned to recharge on the island, as detailed in *The Effects of Withdrawals and Drought on Groundwater Availability in the Northern Guam Lens Aquifer, Guam* (U.S. Geological Survey 2013). Conditions in the Northern Guam Lens Aquifer were considered a reasonable analog for Tinian based on similarities in rainfall, temperature, aquifer geology and topography.

The bottom boundary of the model is no-flow. A constant concentration source of 19,000 milligrams per liter of chloride (representing salt) was assigned approximately 1.5 miles offshore of the island in all layers and in layer 8 beneath the island. The 1.5-mile distance was considered sufficient to prevent boundary effects while maintaining the constant concentration source. Constant concentration cells are shown in Figure 11.



Two-Layer Model



Eight-Layer Model

Model cross section, Row 56, vertical exaggeration = 3x, horizontal coordinates/distances and vertical elevation in meters

Model Cross Sections

0 4,000 8,000 12,000 Feet

Meters 0 600 1,200 1,800 2,400 3,000

PREPARED BY:
AECOM on behalf of
Naval Facilities Engineering Command,
Pacific

All data shown is considered unclassified-sensitive for aggregation, reproduction, distribution, publication, or exhibition and its use is strictly prohibited without the consent of Naval Facilities Engineering Command, Pacific (NAVFAC PAC).

Date: 9/19/2017

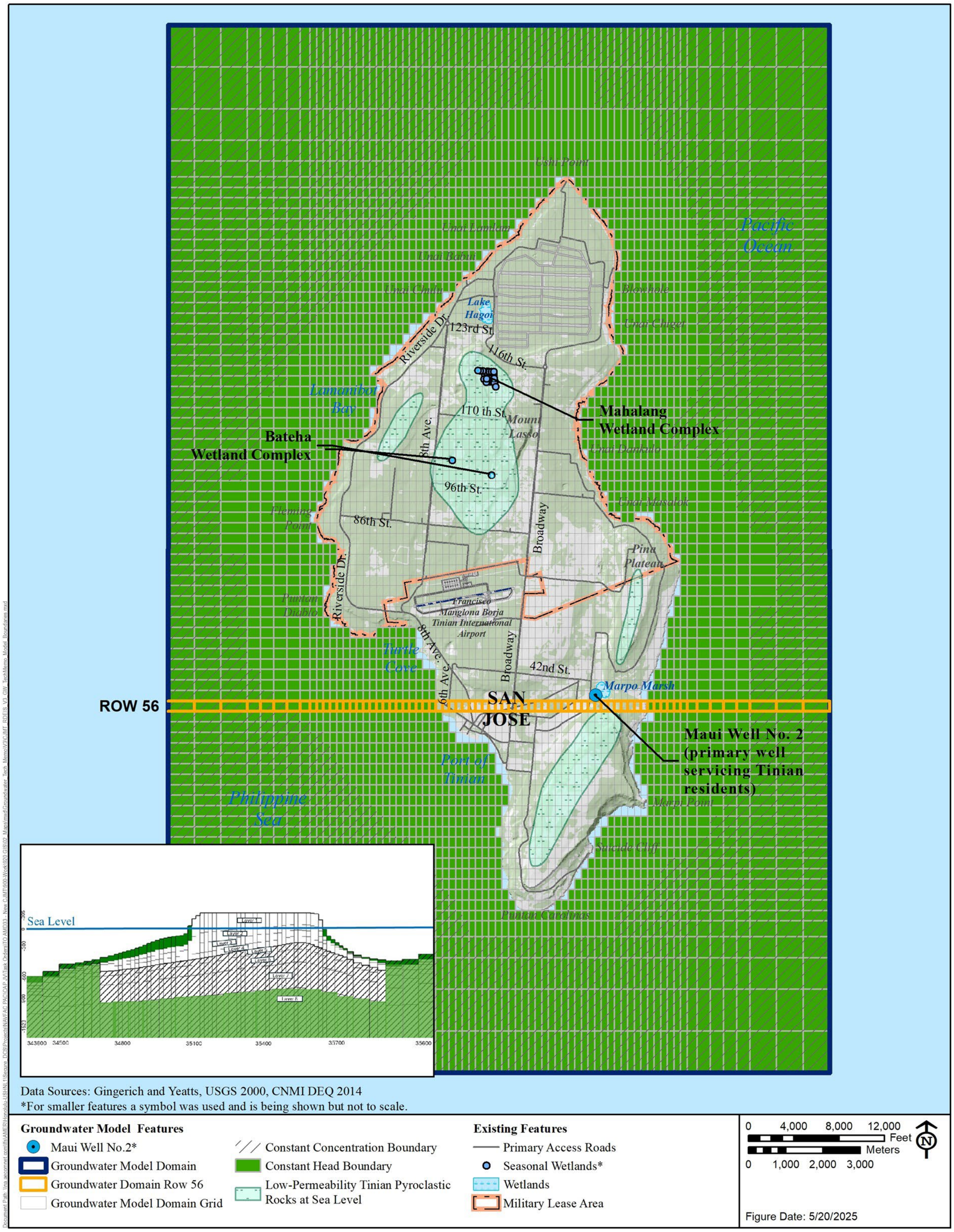
Coordinate System: UTM Zone 55 North
Projection: Transverse Mercator
Datum: D WGS 84

Path: C:\projects\Tinian\GIS\mxds\deliverables\model xsect.mxd

LEGEND

Not Applicable

Figure 10 Model Cross Sections



Data Sources: Gingerich and Yeatts, USGS 2000, CNMI DEQ 2014
*For smaller features a symbol was used and is being shown but not to scale.

Figure 11 Model Boundaries

5.2.3 Hydraulic Parameters

The hydraulic conductivities used in the 2002 U.S. Geological Survey model are as follows:

- High hydraulic conductivity zone representing limestone: 10,500 feet per day
- Lower hydraulic conductivity zone representing clay-rich limestone: 800 feet per day
- Low permeable zone representing the volcanic rocks: 0.2 feet per day

In the 2025 AECOM model, the hydraulic conductivity values in the high hydraulic conductivity zone representing limestone was distributed spatially, while hydraulic conductivity values in the low hydraulic conductivity zone representing clay-rich limestone and in the low hydraulic conductivity zone representing the volcanic rocks were applied uniformly. The hydraulic conductivity values in the 2002 U.S. Geological Survey model were applied to the new model and used as a starting point for calibration; the final hydraulic conductivity values were determined from model calibration.

5.3 FLOW MODEL CALIBRATION

5.3.1 Overview

Model calibration involves adjusting model parameters to achieve a reasonable match with observed data. Care was taken to avoid assigning unreasonable values to any parameter, preventing unrealistic model results. The goal of calibration is to achieve a match, as close as possible, between simulated and observed heads rather than replicate field conditions exactly. A model is generally considered well calibrated for flow when the normalized root mean squared error is less than 10 percent between modeled and measured groundwater elevations for a set of data.

5.3.2 Steady State

Similar to U.S. Geological Survey 2002 model (two-layer model), the AECOM 2025 model (eight-layer model) was also calibrated to “steady state.” The pilot-point interpolation method was used to calibrate the hydraulic conductivity distribution in the high-hydraulic conductivity limestone zone and recharge distribution in all limestone areas. The zonal method was used to calibrate K values in the low- hydraulic conductivity zone representing clay-rich limestone and in low-permeable zone representing the volcanic rocks. Average groundwater levels observed from 1990 to 1999, sourced from the 2002 U.S. Geological Survey model, were used for calibrating AECOM’s 2025 model and are presented in Table 5. The USGS modified these water levels to account for tidal influences per the method outlined in the 2002 report. Calibration results of both the 2002 U.S. Geological Survey model and the 2025 AECOM model are shown are in Table 4. The measured and modeled water levels compare favorably. The head residuals of the 2025 AECOM calibration model are shown in Figure 12 and in Table 5. Figure 13 presents a scatter plot of simulated and measured water levels from the 2025 AECOM calibration. The plot shows a similar spread among all the data sets around the best fit line, indicating a strong correlation between simulated and observed values. Calibration statistics show a mean error close to zero, with a normalized error of 8.66 percent (root mean square error divided by the range of observed heads) well within the calibration criterion of 10 percent. Therefore, the 2025 AECOM model is considered to be well-calibrated and adequate for the intended purposes. Model limitations are discussed in Section 5.8. A summary of calibration statistics is presented in Table 6.

Both the 2002 U.S. Geological Survey model and the 2025 AECOM model produced similar calibration statistics and groundwater contours. Some of the discrepancies can be attributed to differences in model code and construction combined with sparse data. From this point forward, only the 2025 AECOM model was used for simulations.

The final calibrated hydraulic conductivity values of the 2025 AECOM model are as follows:

- High hydraulic conductivity zone representing limestone: 164–13,123 feet per day
- Lower hydraulic conductivity zone representing clay-rich limestone: 115 feet per day
- Low permeable zone representing the volcanic rocks: 0.17–0.53 feet per day

These values are presented in Figure 14. The high hydraulic conductivity values for limestone falls into the range of the aquifer test results (U.S. Geological Survey 2002). Transverse and longitudinal hydraulic conductivity were set equal to one another (no horizontal anisotropy). Vertical hydraulic conductivity was set equal to one-tenth horizontal hydraulic conductivity (horizontal to vertical anisotropy equal 10) as with the U.S. Geological Survey 2002 model. Although the calibrated values varied from the 2002 U.S. Geological Survey model, they are still within the range of values reported from aquifer pump testing on the existing wells. While the pump test results may understate regional hydraulic conductivities in a triple porosity system, the goodness of fit for heads indicates these calibrated values are appropriate for their intended purpose.

In the 2025 AECOM model, the uniform recharge rate of 29.7 inches per year used in the U.S. Geological Survey 2002 model was replaced with a spatially distributed recharge rates, with low-permeability rock areas receiving a minimal recharge rate. Using a pilot-point method, the overall recharge distribution was calibrated to maintain the same total annual recharge volume within the island. The final recharge rate distribution was determined through model calibration. The final calibrated recharge distribution is shown in Figure 15. The model used the following values uniformly across the domain: specific storage (1.52E-06 1/foot) and specific yield and effective porosity (28 percent).

Table 4. Measured and Calculated Water Levels

Well	***Measured Water Levels***	***2002 USGS (Two-Layer) Model Calculated Water Level***	***2025 AECOM (Eight-Layer) Model Calculated Water Level***
	ft msl	***ft msl***	***ft msl***
M-02	2.65	2.62	2.81
M-05	0.93	1.07	1.23
M-07	1.38	1.51	1.53
M-08	1.31	1.41	1.52
M-09	1.40	1.36	1.30
M-10	0.84	0.75	0.56
M-11	1.63	1.43	1.52
M-15	1.30	1.19	1.23
M-16	1.26	1.36	1.43
M-19	2.15	2.18	2.14
M-21	1.62	1.65	1.52
M-22	1.38	1.36	1.40
M-25	1.36	1.27	1.27
M-26	1.77	1.39	1.45
M-29	1.64	1.53	1.69
M-33	1.58	1.45	1.51
M-35	2.42	2.58	2.58
M-39	2.02	2.11	1.87
Municipal (a.k.a. Maui Well No. 1)	1.03	1.03	1.28
HagN	1.13	0.9	1.04
HagS	1.17	0.97	1.06
TH-01	1.11	1.29	1.41
TH-02	0.92	0.86	0.85
TH-04	1.30	1.19	1.30
TH-06	1.22	1.3	1.39
TH-07	1.29	1.36	1.45
TH-09	1.25	1.07	1.22
TH-10	1.27	1.29	1.41
TH-12	1.37	1.33	1.33
TH-22	1.25	1.05	1.14
Ushi	0.78	0.72	0.54

Legend: AECOM = AECOM Technical Services, Inc.; ft = foot/feet; msl = mean sea level; No. = Number.
Source: U.S. Geological Survey 2002 DON.

Table 5. Calculated Differences Between Measured and Modeled Results

Well	*Dates of Measurement*	*Number of Measurements*	*2002 USGS (Two-Layer) Model*	*2025 AECOM (Eight-Layer) Model*
M-02	September 25, 1997–April 16, 1999	15,700	0.03	-0.16
M-05	July 31, 1997–October 1, 1997	3	-0.14	-0.30
M-07	July 6, 1995–October 1, 1997	25	-0.13	-0.15
M-08	August 22, 1997–October 3, 1997	3	-0.10	-0.21
M-09	May 4, 1995–October 2, 1997	31	0.04	0.10
M-10	March 31, 1997–December 29, 1997	8	0.09	0.28
M-11	April 13, 1995–December 29, 1997	34	0.20	0.11
M-15	May 29, 1997–December 29, 1997	6	0.11	0.07
M-16	May 4, 1995–December 29, 1997	32	-0.10	-0.17
M-19	June 5, 1997–December 30, 1997	5	-0.03	0.01
M-21	September 30, 1990–February 1, 1996	45,443	-0.03	0.10
M-22	July 4, 1997–December 30, 1997	5	0.02	-0.02
M-25	November 1, 1994–September 5, 1997	28	0.09	0.09
M-26	November 1, 1994–September 5, 1997	20	0.38	0.32
M-29	July 30, 1997–April 16, 1999	14,524	0.11	-0.05
M-33	August 22, 1997–December 30, 1997	4	0.13	0.07
M-35	July 31, 1997–December 30, 1997	4	-0.16	-0.16
M-39	May 15, 1997–December 30, 1997	7	-0.09	0.15
Municipal (Maui Well No. 1)	November 22, 1990–April 16, 1999	67,952	0.00	-0.25
HagN	May 17, 1993–July 4, 1997	39	0.23	0.09
HagS	May 17, 1993–July 4, 1997	38	0.20	0.11
TH-01	September 17, 1996–December 29, 1997	4	-0.18	-0.30
TH-02	April 30, 1997–September 5, 1997	5	0.06	0.07
TH-04	January 10, 1994–December 29, 1997	48	0.11	0.00
TH-06	July 6, 1995–July 31, 1997	27	-0.08	-0.17
TH-07	September 17, 1997–April 16, 1999	9,233	-0.07	-0.16
TH-09	February 9, 1993–December 30, 1997	114	0.18	0.03
TH-10	October 10, 1996–December 29, 1997	18	-0.02	-0.14
TH-12	January 8, 1997–December 29, 1997	10	0.04	0.04
TH-22	October 31, 1996–December 29, 1997	17	0.20	0.11
Ushi	October 1, 1990–July 28, 1997	53,296	0.06	0.24

Legend: AECOM = AECOM Technical Services, Inc.; No. = Number; USGS = United States Geological Survey.

Table 6. Statistics of 2025 AECOM (Eight-Layer) Model

Mean Error	-0.01
Mean Absolute Error	0.14
Root Mean Square Error	0.16
Maximum Observed Head	2.65
Minium Observed Head	0.78
Range of Observed Heads	1.87
Normalized Error (Root Mean Square Error divided by Head Range)	8.66%
Correlation Coefficient between Observed and Modeled Heads	93.58%

Legend: % = percent; AECOM = AECOM Technical Services, Inc.

*For smaller features a symbol was used and is being shown but not to scale.

Data Sources: USGS 2000, CNMI DEQ 2014

Figure Date: 5/20/2025

Figure 12 Model Head Residuals

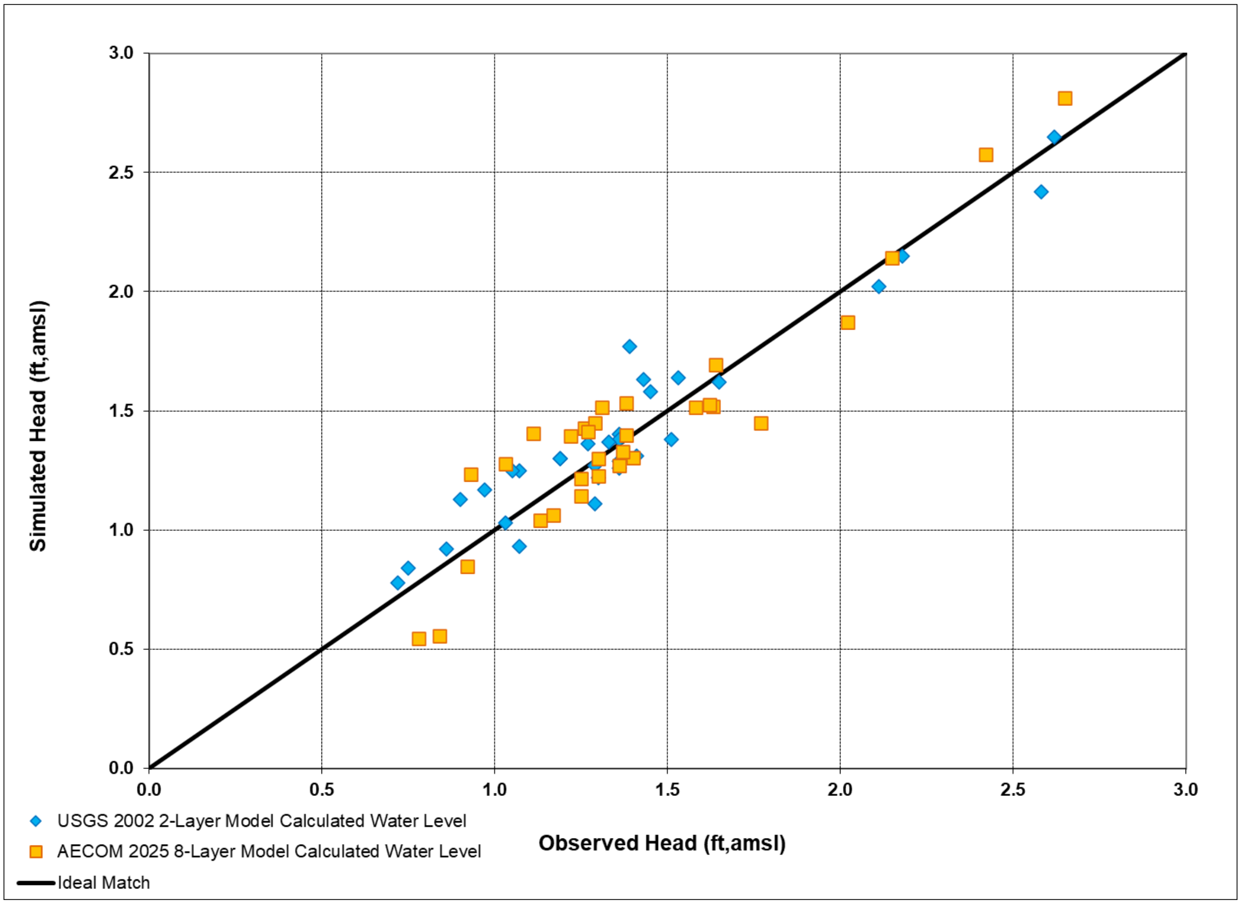
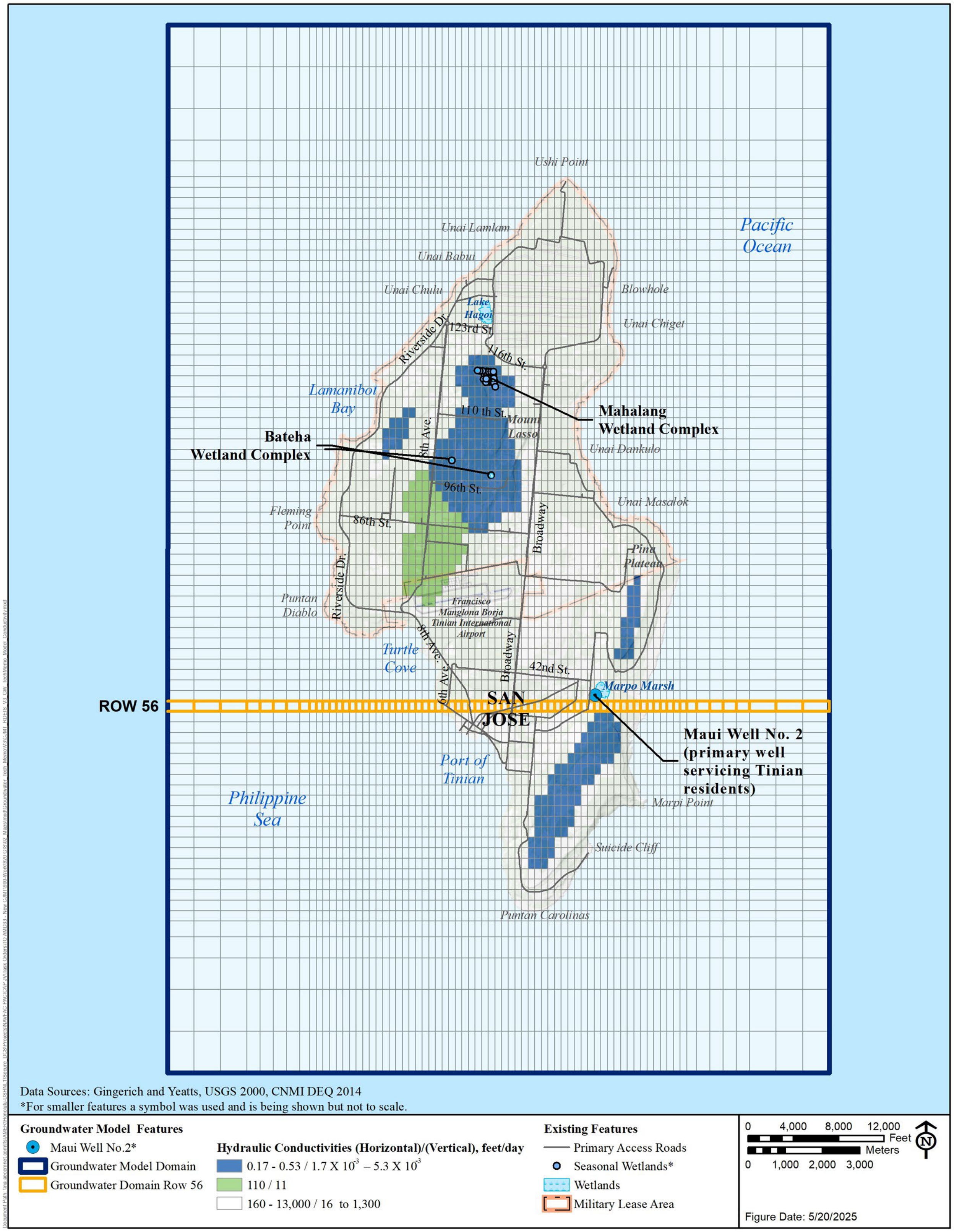
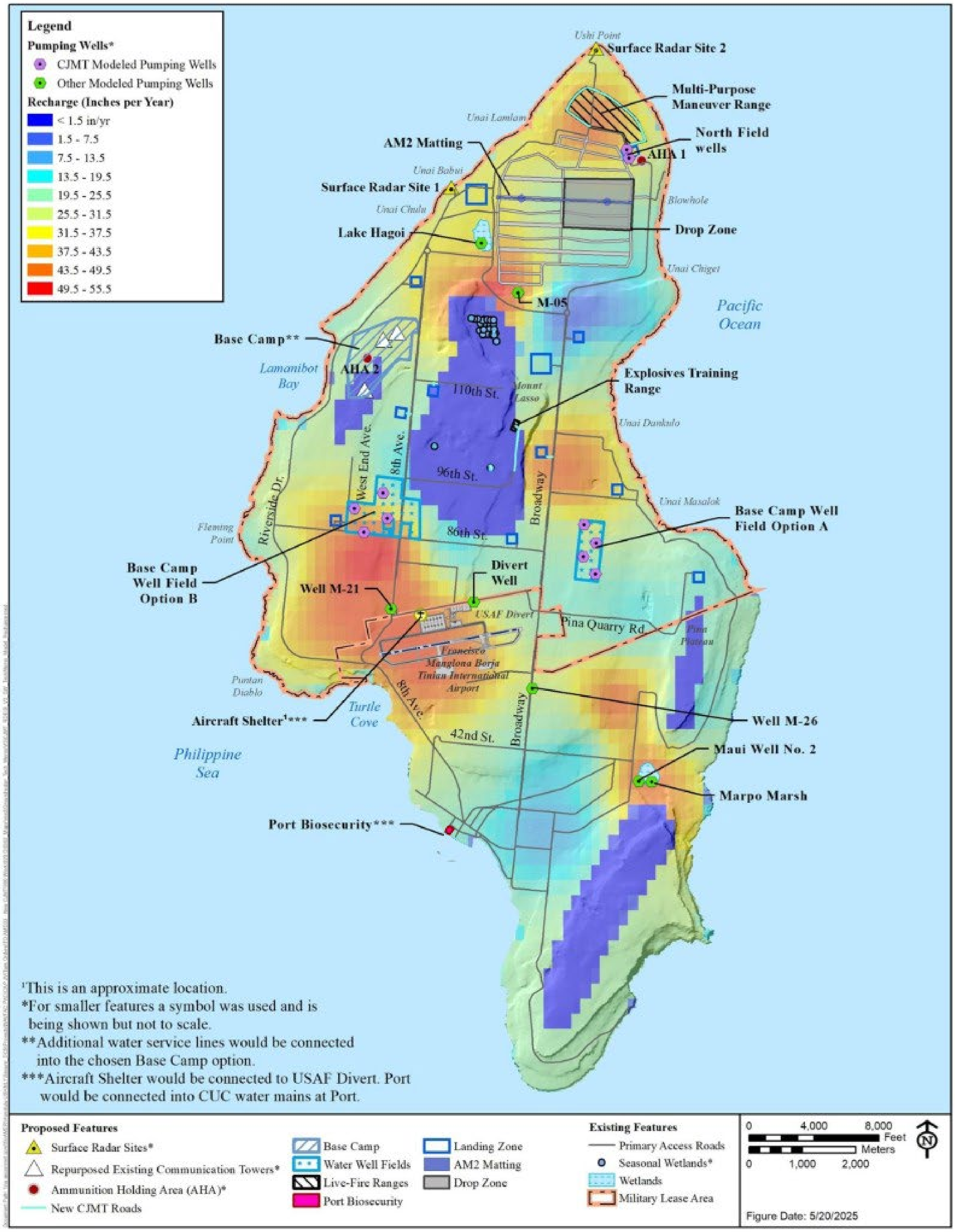


Figure 13 Scatter Plot of Observed Heads vs. Simulated Heads



Data Sources: Gingerich and Yeatts, USGS 2000, CNMI DEQ 2014
*For smaller features a symbol was used and is being shown but not to scale.

Figure 14 Model Hydraulic Conductivity Values and Distribution in Model Layer 1



¹This is an approximate location.

*For smaller features a symbol was used and is being shown but not to scale.

**Additional water service lines would be connected into the chosen Base Camp option.

***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure Date: 5/20/2025

Figure 15 Model Recharge

5.4 MODEL SCENARIOS

The next step in the process was to run the model in a transient state using the SEAWAT module in the GMS modeling platform. An initial model run was conducted to establish steady-state conditions with regard to saltwater distribution. Prior to applying pumping conditions to the model, it is necessary to establish a steady-state baseline. The simulation time typically exceeds 100 years before equilibrium is reached, depending on several factors, including the defined initial concentrations. Steady state in this context refers to a stabilized condition in the flow and transport system, not the model code. The system was deemed to be at "steady state" when the modeled hydraulic heads and concentrations ceased to change over time throughout the model domain. The model was run under baseline conditions for 250 years to approximate steady state. Following this, the model ran for 250 years to simulate each of the scenarios (forward simulations).

The drought scenario was assumed to be two consecutive years of reduced rainfall, represented in the model by a conservative infiltration rate of 10 percent of the modeled normal infiltration rate. Drought conditions were applied for a period of 2 years of reduced recharge during model years 249 and 250. Model results discussed below refer to the end of the 250-year forward simulation periods. In SEAWAT, salt concentrations are modeled at the center of a model cell, unlike the SHARP code that calculates an interface between salt and freshwater with no diffuse concentrations above or below the modeled boundary. Note that model layering is different from aquifer or geologic layering. In this model, the layers are numbered from top to bottom (i.e., layer 1 is the shallowest and layer 8 is the deepest). The top three model layers (layers 1 through 3) represent the limestone aquifer system and the remaining five layers (4 through 8) represent the low-permeability volcanic material. Figure 16 through Figure 20 depict predicted chloride concentrations in model layers 1 through 3. These are the layers containing the existing and proposed well screens. Maui Well No. 2 and the CJMT wells were assigned to model layer 1.

The five scenarios are below; italicized text highlights the differences.

Scenario No. 1 (Baseline)

- Normal rainfall.
- Existing Commonwealth Utilities Corporation Water Demand (Maui Well No. 2) = 853,472 gallons per day (Average 2019–2023).
- Well M-21 using Divert construction water demands based on Bureau of Environmental and Coastal Quality permitted pumping limits per September 2024 field notes = 59,178 gallons per day.
- Well M-26 agricultural water demand = 59,178 gallons per day.

Scenario No. 2 (Proposed Action + Normal Rainfall + Well Field A)

- Normal rainfall.
- Existing Commonwealth Utilities Corporation Water Demand (Maui Well No. 2) = 853,472 gallons per day (taken from average 2019–2023 demand from Commonwealth Utilities Corporation).
- Proposed additional water demand on Commonwealth Utilities Corporation (Maui Well No. 2) due to CJMT = 9,046 gallons per day.

- Well M-21 CJMT construction water demand = 59,178 gallons per day – M-21 to be used for CJMT construction (No Divert and no agricultural at this well).
- Well M-26 agricultural water demand. = 59,178 gallons per day.
- CJMT water demand at *Well Field A* which includes concurrent construction and operational water demands = 21,777 gallons per day.
- Construction water at M-21, *Well Field A* would be 23,340 gallons per day. Will not be separately modeling the post-CJMT-construction demand at the new Well Field A or M-21.
- CJMT water wells at North Field. = 2,192 gallons per day.
- U.S. Air Force North Field construction (M-05) = 12,000 gallons per day.
- Divert Well (firefighting well at Tinian International Airport) = 2,192 gallons per day.

Scenario No. 3 (Proposed Action + Drought Rainfall + Well Field A)

- Drought conditions.
- Existing Commonwealth Utilities Corporation Water Demand (Maui Well No. 2) = 853,472 gallons per day (taken from average 2019 – 2023 demand from Commonwealth Utilities Corporation).
- Proposed additional water demand on Commonwealth Utilities Corporation (Maui Well No. 2) due to CJMT = 9,046 gallons per day.
- Well M-21 CJMT construction water demand = 59,178 gallons per day– M-21 to be used for CJMT construction (No Divert and no agricultural at this well).
- Well M-26 agricultural water demand = 59,178 gallons per day.
- CJMT water demand at *Well Field A* which includes concurrent construction and operational water demands = 21,777 gallons per day.
- Construction water is now at M-21, *Well Field A* would be 23,340 gallons per day. Will not be separately modeling the post-CJMT-construction demand at the new Well Field A or M-21.
- CJMT water wells at North Field = 2,192 gallons per day.
- U.S. Air Force North Field construction (M-05) = 12,000 gallons per day.
- Divert Well (firefighting well at Tinian International Airport) = 2,192 gallons per day.

Scenario No. 4 (Proposed Action + Normal Rainfall + Well Field B)

- Normal rainfall.
- Existing Commonwealth Utilities Corporation Water Demand (Maui Well No. 2) = 853,472 gallons per day (taken from average 2019 – 2023 demand from Commonwealth Utilities Corporation).
- Proposed additional water demand on Commonwealth Utilities Corporation (Maui Well No. 2) due to CJMT = 9,046 gallons per day.
- Well M-21 CJMT construction water demand = 59,178 gallons per day– M-21 to be used for CJMT construction (No Divert and no agricultural at this well).
- Well M-26 agricultural water demand = 59,178 gallons per day.
- CJMT water demand at *Well Field B* which includes concurrent construction and operational water demands = 21,777 gallons per day.

- Construction water is now at M-21, *Well Field B* would be 23,340 gallons per day. Will not be separately modeling the post-CJMT-construction demand at the new Well Field B or M-21.
- CJMT water wells at North Field = 2,192 gallons per day.
- U.S. Air Force North Field construction (M-05) = 12,000 gallons per day.
- Divert Well (firefighting well at Tinian International Airport) = 2,192 gallons per day.

Scenario No. 5 (Proposed Action + Drought Rainfall + Well Field B)

- Drought conditions.
- Existing Commonwealth Utilities Corporation Water Demand (Maui Well No. 2) = 853,472 gallons per day (taken from average 2019 – 2023 demand from Commonwealth Utilities Corporation).
- Proposed additional water demand on Commonwealth Utilities Corporation (Maui Well No. 2) due to CJMT = 9,046 gallons per day.
- Well M-21 CJMT construction water demand = 59,178 gallons per day – M-21 to be used for CJMT construction (No Divert and no agricultural at this well).
- Well M-26 agricultural water demand = 59,178 gallons per day.
- CJMT water demand at *Well Field B* which includes concurrent construction and operational water demands = 21,777 gallons per day.
- Construction water is now at M-21, *Well Field B* would be 23,340 gallons per day. Will not be separately modeling the post-CJMT-construction demand at the new Well Field B or M-21.
- CJMT water wells at North Field = 2,192 gallons per day.
- U.S. Air Force North Field construction (M-05) = 12,000 gallons per day.
- Divert Well (firefighting well at Tinian International Airport) = 2,192 gallons per day.

Pumping and evaporative/evapotranspirative losses from the lake and marsh for each of the scenarios are summarized in Table 7.

Table 7. Pumping Rates for Scenarios 1 through 5

Well	*Scenario 1 (Baseline)*	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*
Lake Hagoi	41,739				
Makpo Marsh	123,897				
Maui Well No. 2	853,472	862,518	862,518	862,518	862,518
M-21	59,178	59,178	59,178	59,178	59,178
M-26	59,178	59,178	59,178	59,178	59,178
M-05	—	12,000	12,000	12,000	12,000
Divert Well	—	2,192	2,192	2,192	2,192
North Field-01	—	2,192	2,192	2,192	2,192
North Field-02	—				
Well Field A-01	—	21,777	21,777	—	—
Well Field A-02	—			—	—
Well Field A-03	—			—	—
Well Field A-04	—			—	—

Well	*Scenario 1 (Baseline)*	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*
Well Field B-01	—	—	—	21,777	21,777
Well Field B-02	—	—	—		
Well Field B-03	—	—	—		
Well Field B-04	—	—	—		

Note: All units in gpd.
Legend: gpd = gallon per day; No. = Number.

5.5 MODEL RESULTS

Modeled pumping for the proposed DoD wells was evenly distributed among the listed wells. Divert construction is expected to be staggered from CJMT construction and is therefore not included. Long-term operational Divert demands are assumed to be incidental at the facility itself. Table 8 summarizes the resulting concentrations in model cells corresponding to the wells of interest, following the figures for each scenario.

Table 8. Predicted Chloride Concentrations for Scenarios 1 through 5

Well	*Scenario 1 (Baseline)*	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*
Maui Well No. 1	32	32	33	32	33
Maui Well No. 2	149	150	168	150	167
M-21	48	48	106	48	107
M-26	32	51	100	51	100
M-05	41	42	70	42	70
Divert Well	32	32	39	32	39
North Field-01	590	590	902	590	902
North Field-02	665	664	1,130	664	1,130
Well Field A-01	37	37	40	37	40
Well Field A-02	35	35	49	35	40
Well Field A-03	32	32	39	32	33
Well Field A-04	34	34	38	34	35
Well Field B-01	30	32	30	30	30
Well Field B-02	30	30	30	30	30
Well Field B-03	30	30	30	30	31
Well Field B-04	30	30	30	30	30

Note: All units in mg/L.
Legend: mg/L = milligram per liter; No. = Number.

Modeled chloride concentrations in model layers 1, 2, and 3 for each scenario are presented in Figure 16 through Figure 20.

Many of these concentrations are not predicted to change or are predicted to change very little as a result of CJMT groundwater extraction. The biggest predicted changes at individual wells are under drought conditions (Scenarios 3 and 5) in M-21, M-26, M-05, North Field-01 and North Field-02, However in all cases wells that currently meet the secondary standard continue to meet that standard. The North Field-01 and North Field-02 are expected to remain non-potable under normal and drought conditions. To evaluate the reasonableness of these results, data from the *Aquifer Study Technical Memorandum* (DON 2015) were reviewed. These included data from U.S. Geological Survey 2000, U.S. Geological Survey 2002, and DON (2015). These are summarized in Table 9 and Table 10. In both data sets, chloride concentrations were measured before and after single-day to multi-day pump tests.

Consistent with the current modeling results, during the 2015 aquifer study, wells M-21, M-25, and M-33 saw little to no change in chloride concentrations before and after pumping (Table 9). Additional data before and after pumping (Table 10) indicate that most locations (nine wells) did not change in chlorides before or after pumping. Two locations decreased in chloride concentrations and four locations increased in chloride concentrations.

Table 9. 2015 Aquifer Study Chloride Concentrations

Well	*Average Pumping Rate (gpm)*	*Maximum Drawdown During Pumping (ft)*	*Pre-Pumping Chloride Concentration (mg/L)*	*Post-Pumping Chloride Concentration (mg/L)*
M-21	31	0.12	220	220
M-25	112	0.25	720	710
M-33	104	1.92	39	44

Legend: ft = foot/feet; gpm = gallon per minute; mg/L = milligram per liter.
Source: DON 2015.

Table 10. Chloride Concentrations Observed Before and After Pumping

Well	*Observed Chlorides Before Pumping (mg/L)*	*Observed Chlorides After Pumping (mg/L)*	*Differences in Chlorides (mg/L)*
Ag30	130	130	0
HagS	148	160	12
M-08	100	600	500
M-15	35	70	35
M-16	106	45	-61
M-21	220	220	0
M-25	720	710	-10
M-33	39	44	5
Maui Well No. 1	100	100	0
Pala	200	200	0
W-1	85	85	0
W-14	40	40	0
W-20	600	600	0
W-4	35	35	0
W-6	100	100	0

Legend: No. = Number; mg/L = part per million.
Source: USGS 2000; DON 2015.

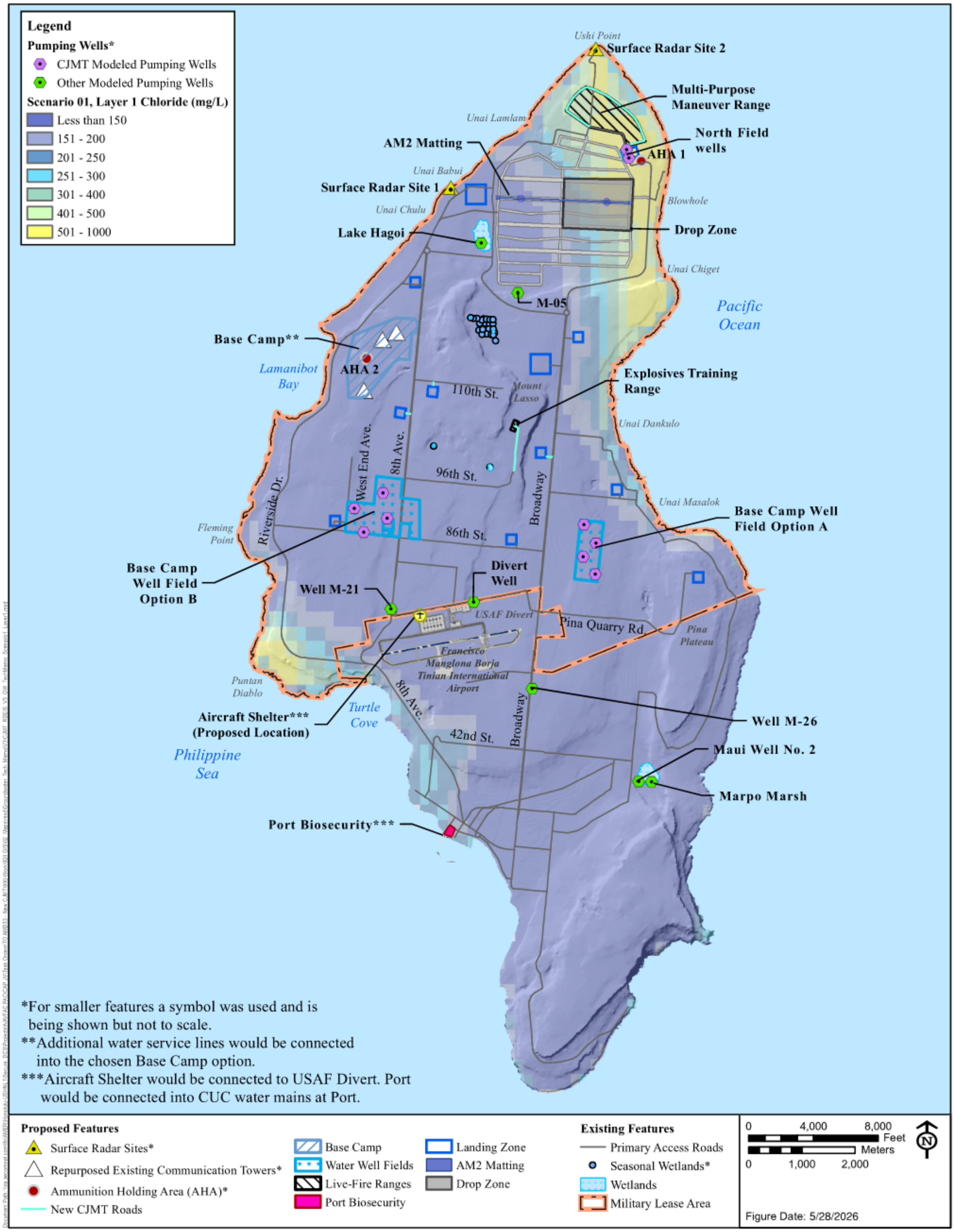
In both data sets (Table 9 and Table 10), many of the wells exhibited little to no chloride concentration change as a result of single-day to multi-day testing.

The Ushi and M-05 wells in the North Field area were pump tested for 36 hours each in November 2025 (APEC 2025). Water quality testing was performed during this pump testing. Water from these wells exceeded primary and secondary drinking water standards (e.g., for chloride, total dissolved solids and coliform bacteria). The water also exceeded the chloride limits for reinforced concrete mixing water. The wells were pumped at 35 to 40 gpm each. Water levels fluctuated up to 0.23 and 0.05 feet in Ushi and M-10, respectively. However, based on the sinusoidal shape of the water level plots, much of this fluctuation may be due to tidal fluctuation. Chloride concentrations were reported to vary between 2,352 and 2,499 mg/L, and 2,058 and 2,499 mg/L for Ushi and M-10, respectively during the tests with no distinct pattern of increase or decrease in either well during pumping. These values are roughly an order of magnitude from the value reported at the end of pumping by Doan et al 1960, indicating large fluctuations over the years. The modeling assumed that groundwater for U.S. Air Force use would come from the M-05 wells farther to south and closer to the center of the island. The modeling assumed CJMT pumping in the North Field area at 2 wells (designated North Field-01 and North Field-02) located southeast of Ushi and M-10. Model results indicate that water at these wells is expected to be brackish and increase in salinity during drought conditions.

The modeling conclusions appear to be reasonable on the whole. However, some locations (especially those with vertical conduits that extend below the saltwater-freshwater interface) may exhibit rapid salinity increases. For that reason, Section 6 includes recommendations for pump testing and water quality testing. If some wells are observed to exhibit rapid salinity increases, those wells should be properly plugged and abandoned under permit from CNMI Bureau of Environmental and Coastal Quality.

5.6 GROUNDWATER FLOW DIRECTIONS

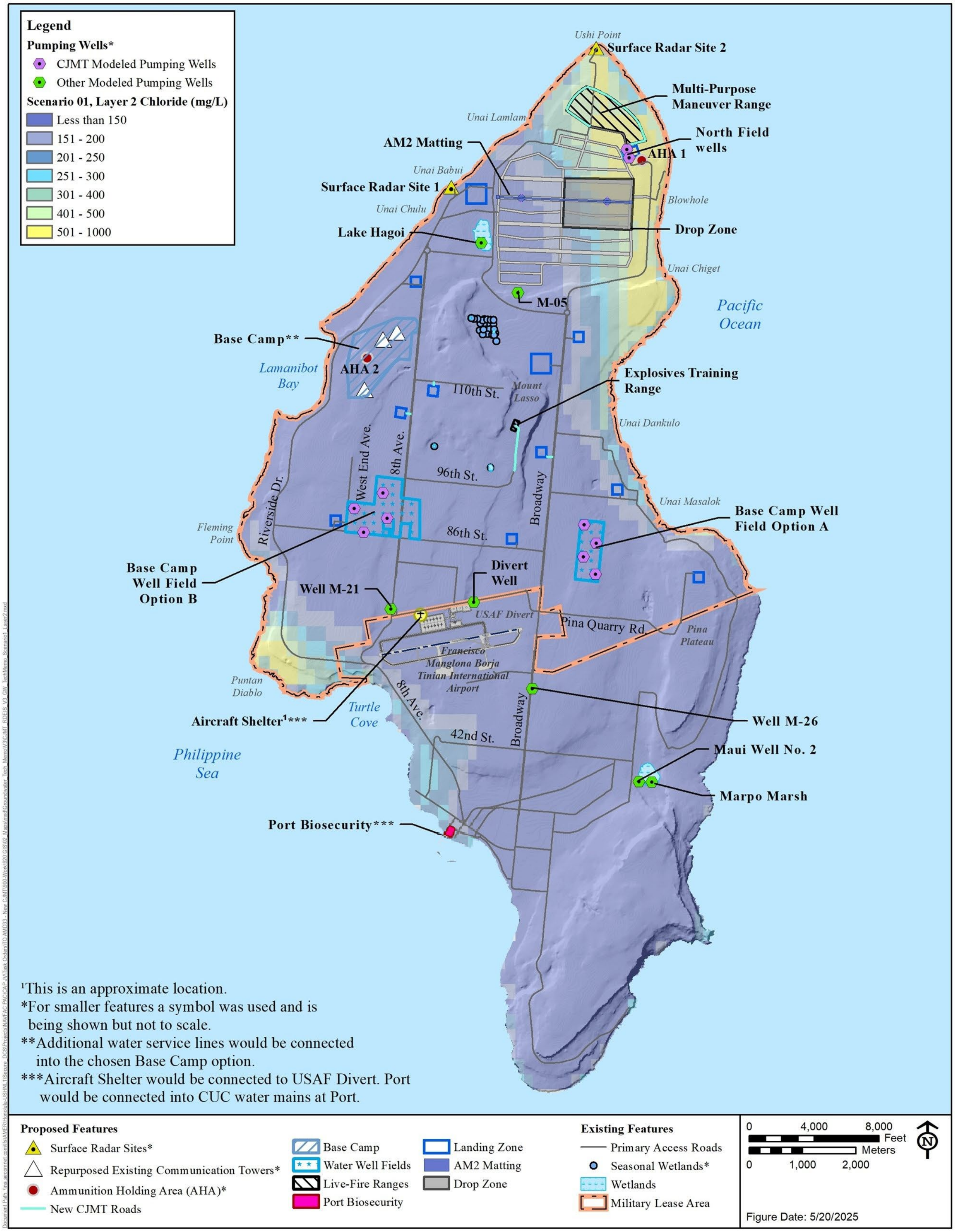
Modeled groundwater heads and groundwater flow directions under current (baseline) conditions (Scenario 1) and the proposed action under drought conditions (Scenarios 3 and 5) are plotted in Figure 21 through Figure 23. The baseline contours differ slightly from the proposed action under drought conditions. There are also slight differences between pumping at Well Field A (Scenario 3) versus pumping at Well Field B (Scenario B) but not enough to noticeably alter contours.



*For smaller features a symbol was used and is being shown but not to scale.
**Additional water service lines would be connected into the chosen Base Camp option.
***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure Date: 5/28/2026

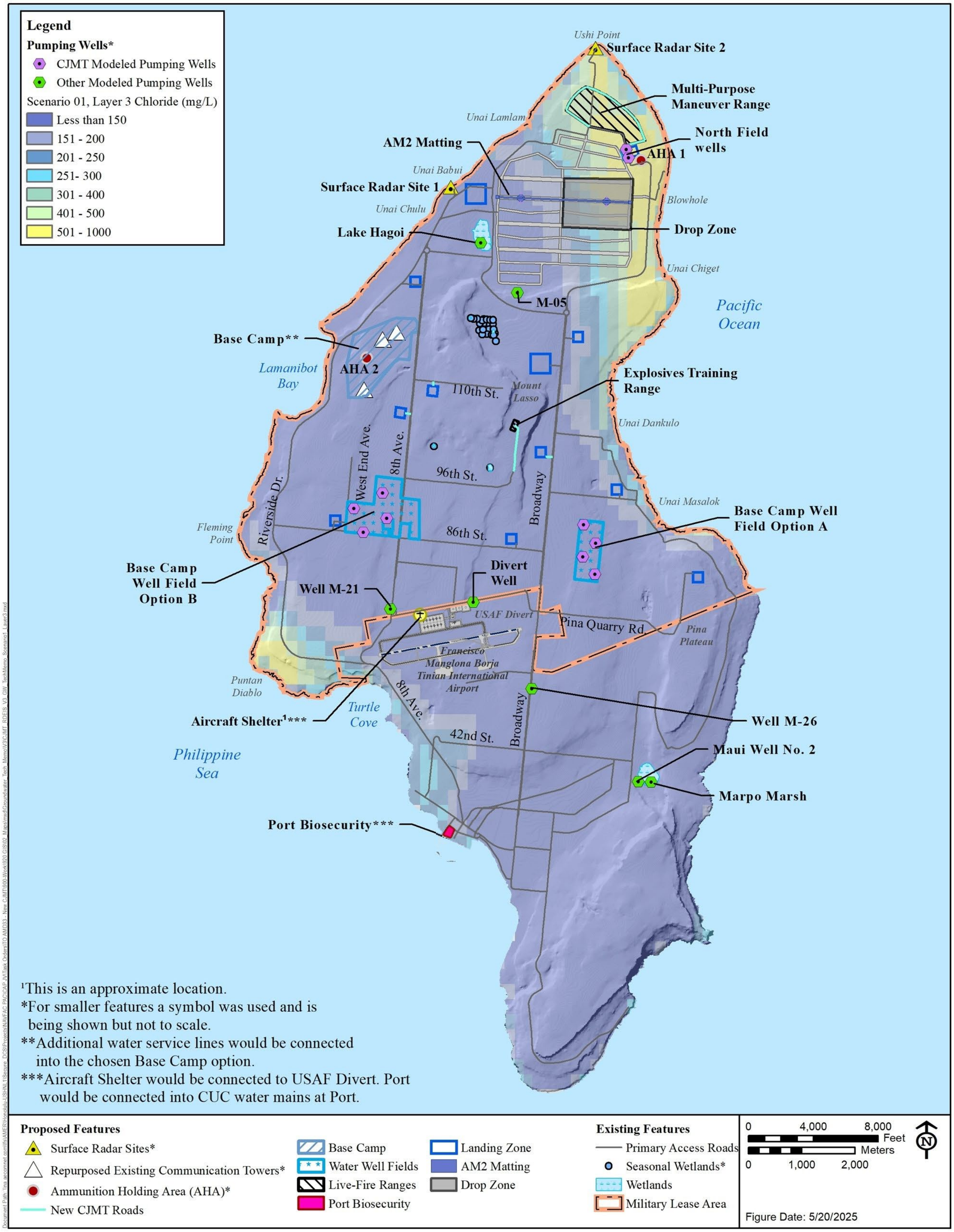
Figure 16.1 Modeled Chloride Concentrations for Layer 1 – Scenario 1



¹This is an approximate location.
*For smaller features a symbol was used and is being shown but not to scale.
**Additional water service lines would be connected into the chosen Base Camp option.
***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure Date: 5/20/2025

Figure 16.2 Modeled Chloride Concentrations for Layer 2 – Scenario 1



¹This is an approximate location.
*For smaller features a symbol was used and is being shown but not to scale.
**Additional water service lines would be connected into the chosen Base Camp option.
***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure Date: 5/20/2025

Figure 16.3 Modeled Chloride Concentrations for Layer 3 – Scenario 1

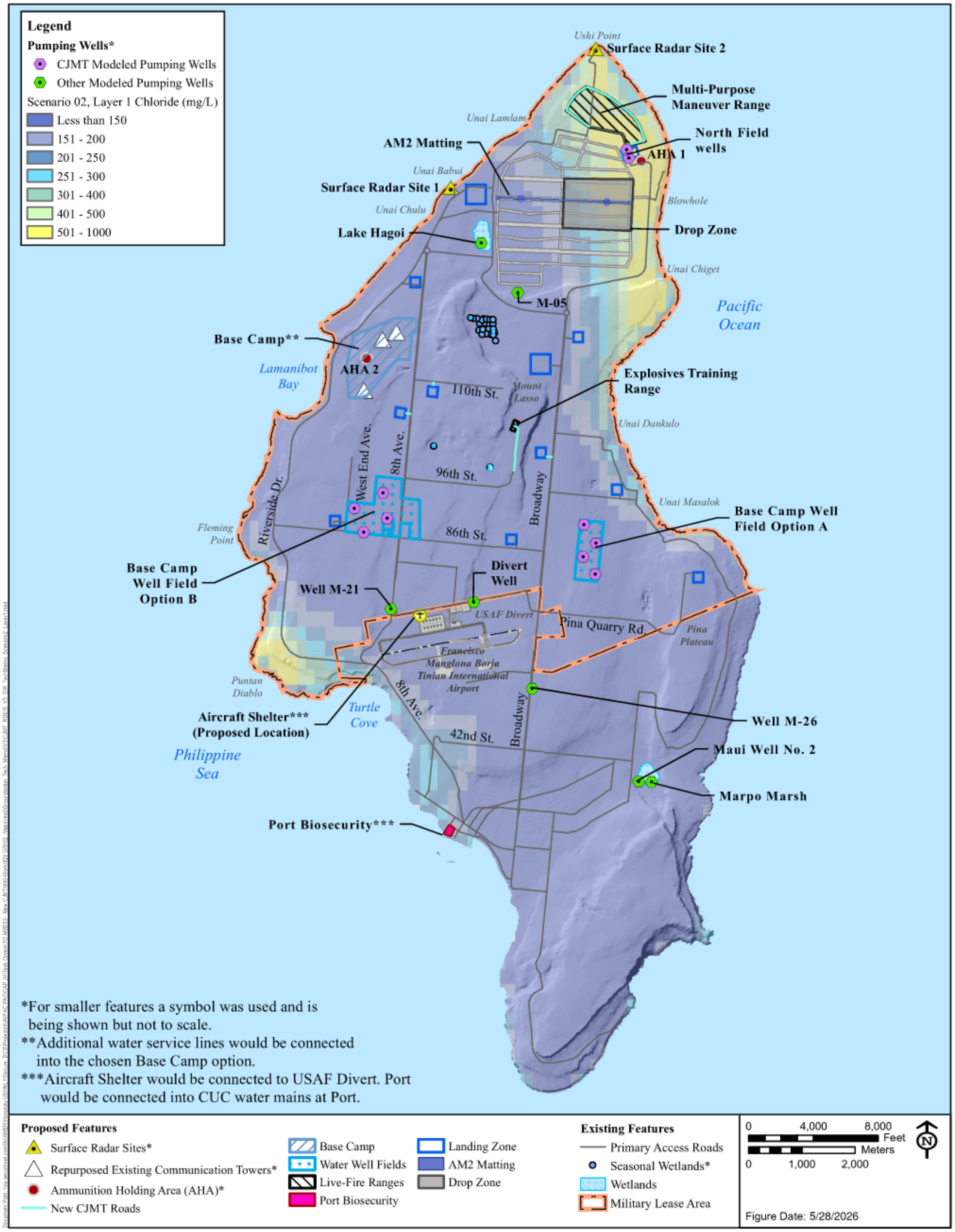
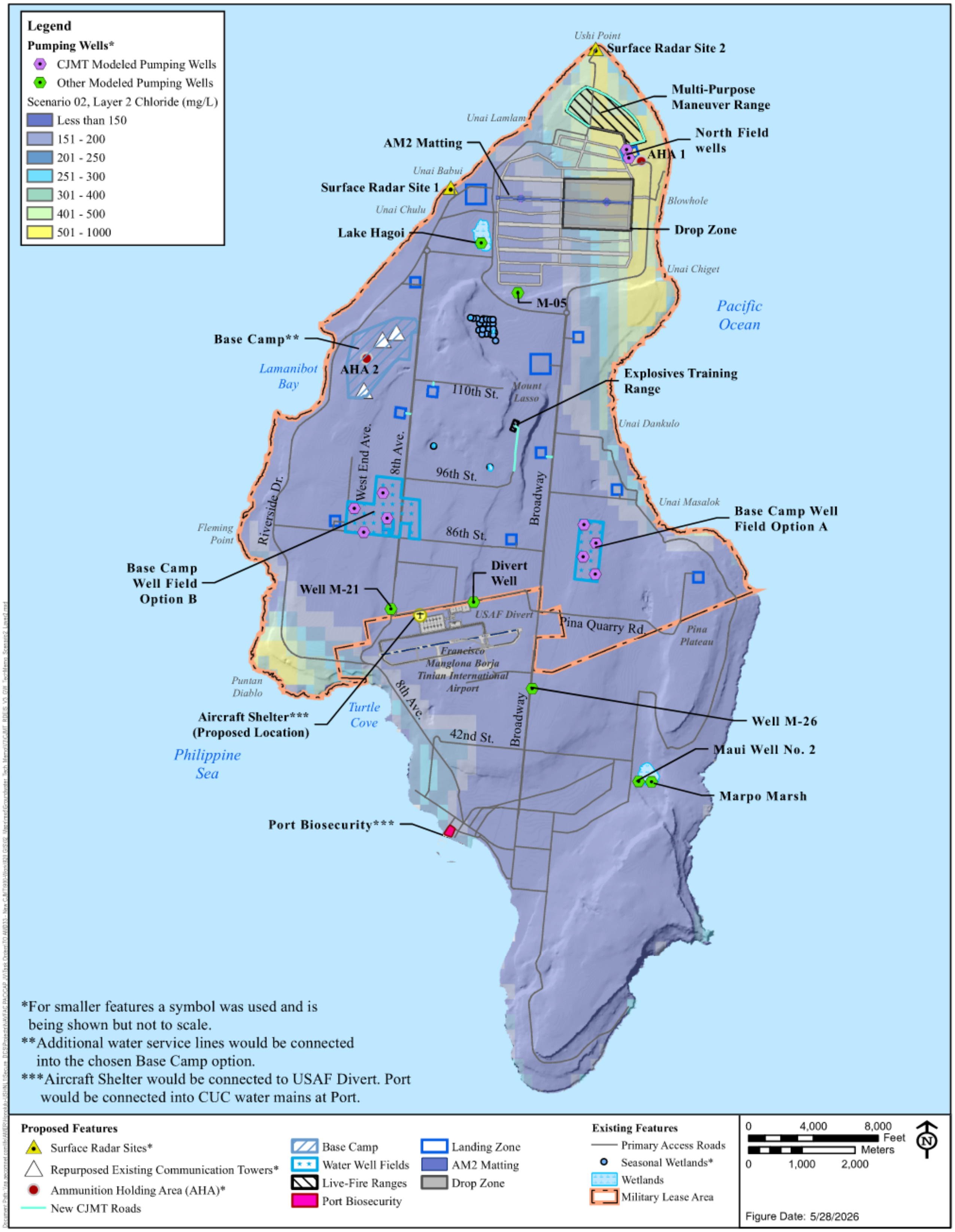


Figure 17.1 Modeled Chloride Concentrations for Layer 1 – Scenario 2



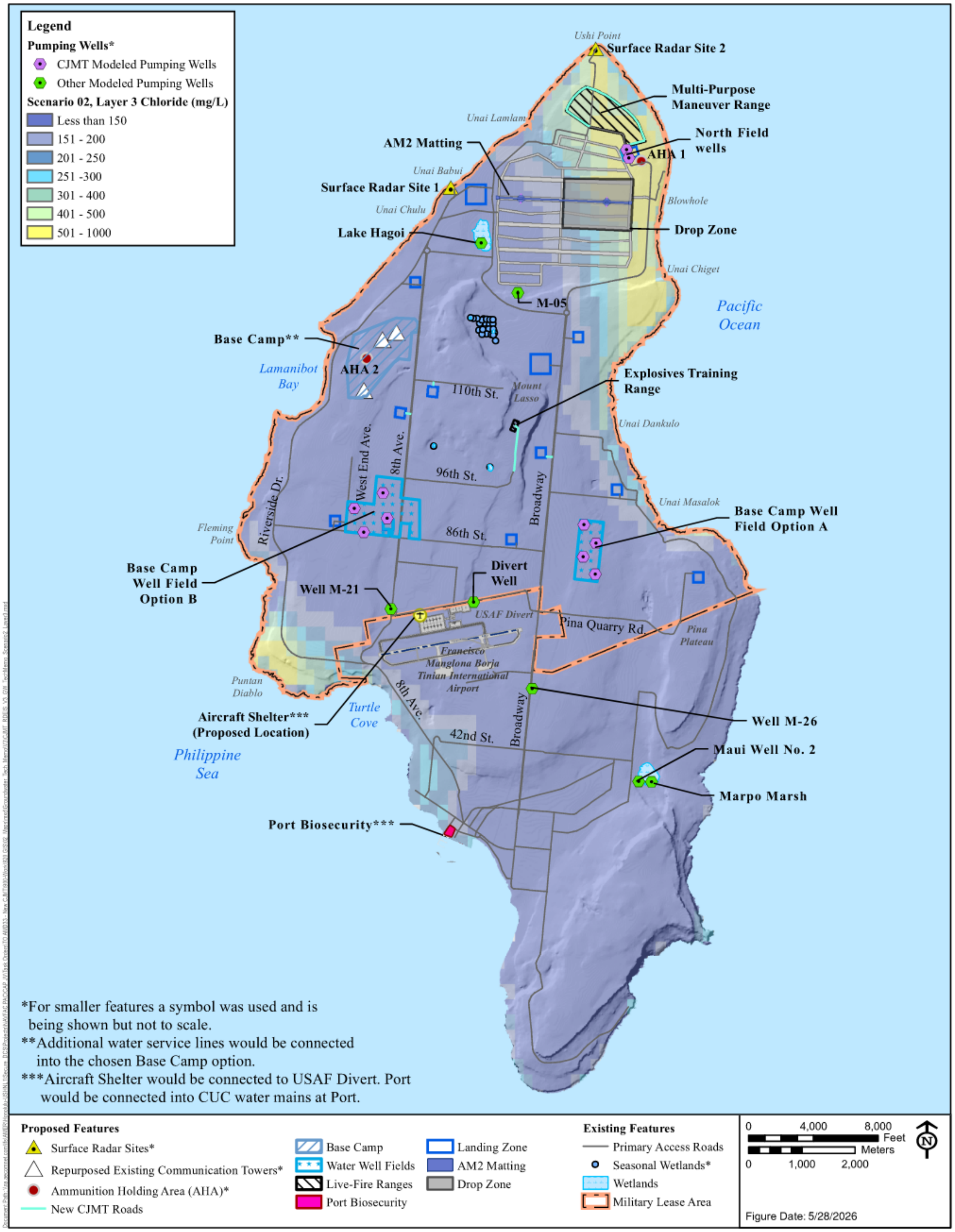
*For smaller features a symbol was used and is being shown but not to scale.

**Additional water service lines would be connected into the chosen Base Camp option.

***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure Date: 5/28/2026

Figure 17.2 Modeled Chloride Concentrations for Layer 2 – Scenario 2



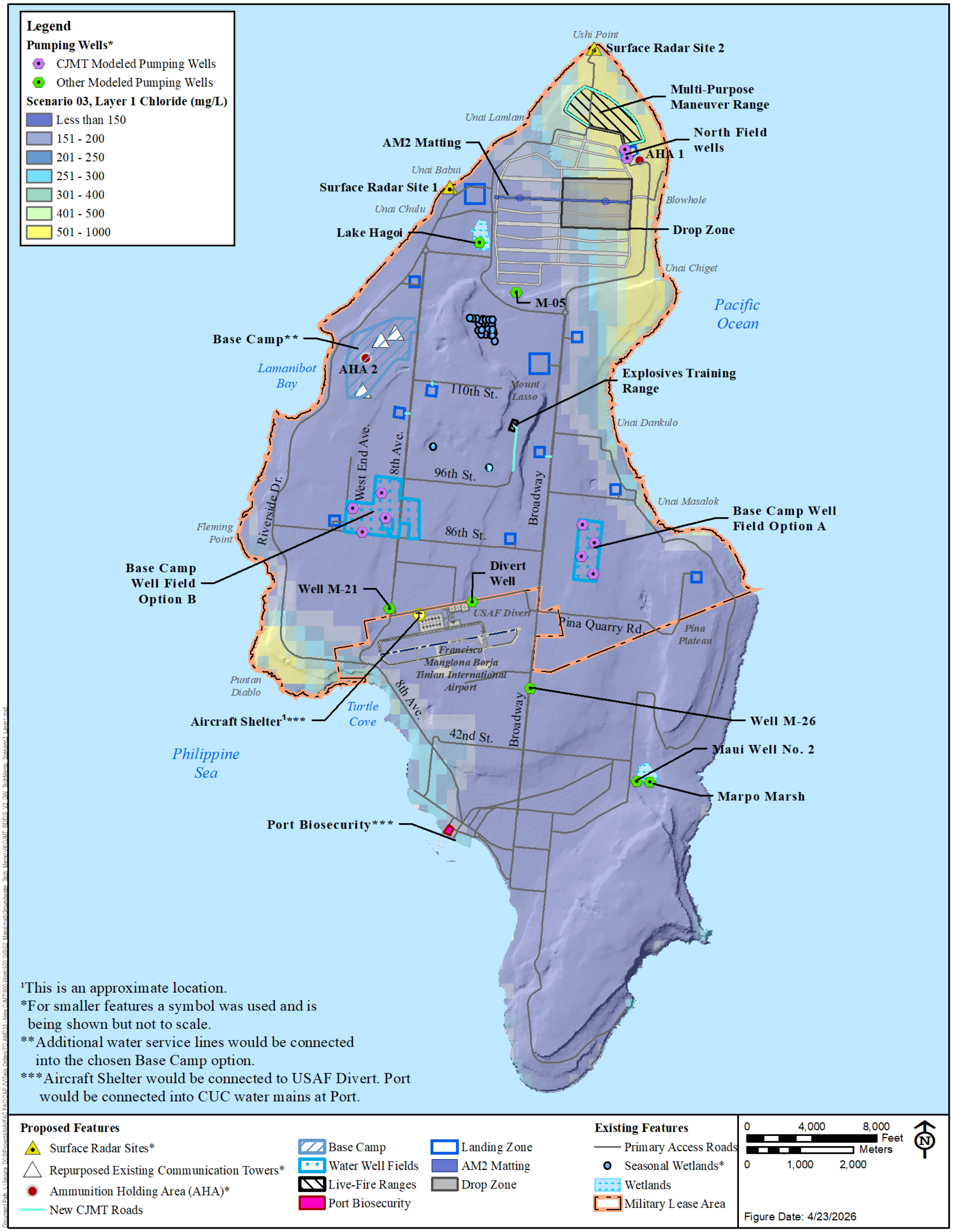
*For smaller features a symbol was used and is being shown but not to scale.

**Additional water service lines would be connected into the chosen Base Camp option.

***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure Date: 5/28/2026

Figure 17.3 Modeled Chloride Concentrations for Layer 3 – Scenario 2



¹This is an approximate location.
*For smaller features a symbol was used and is being shown but not to scale.
**Additional water service lines would be connected into the chosen Base Camp option.
***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure Date: 4/23/2026

Figure 18.1 Modeled Chloride Concentrations for Layer 1 – Scenario 3

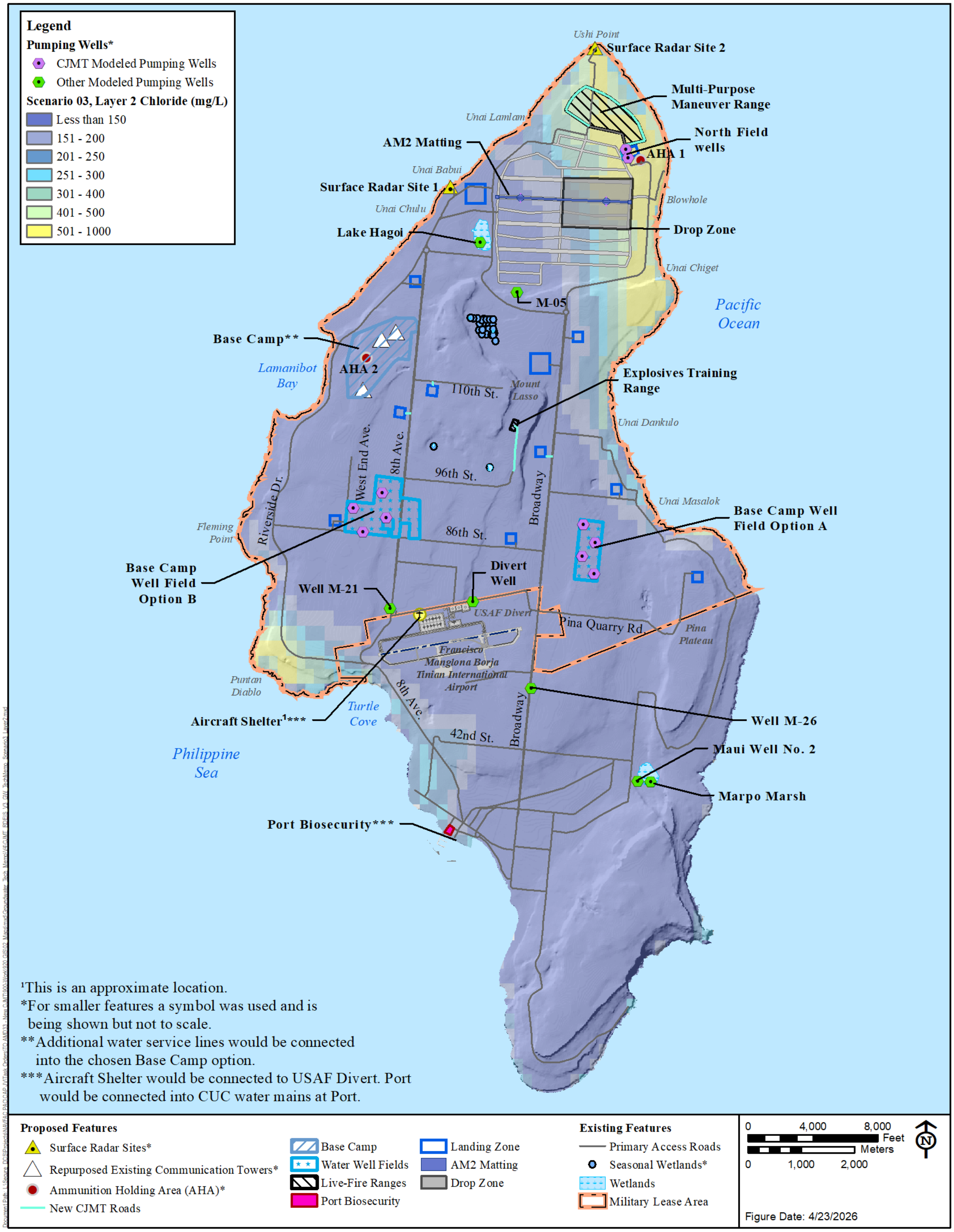
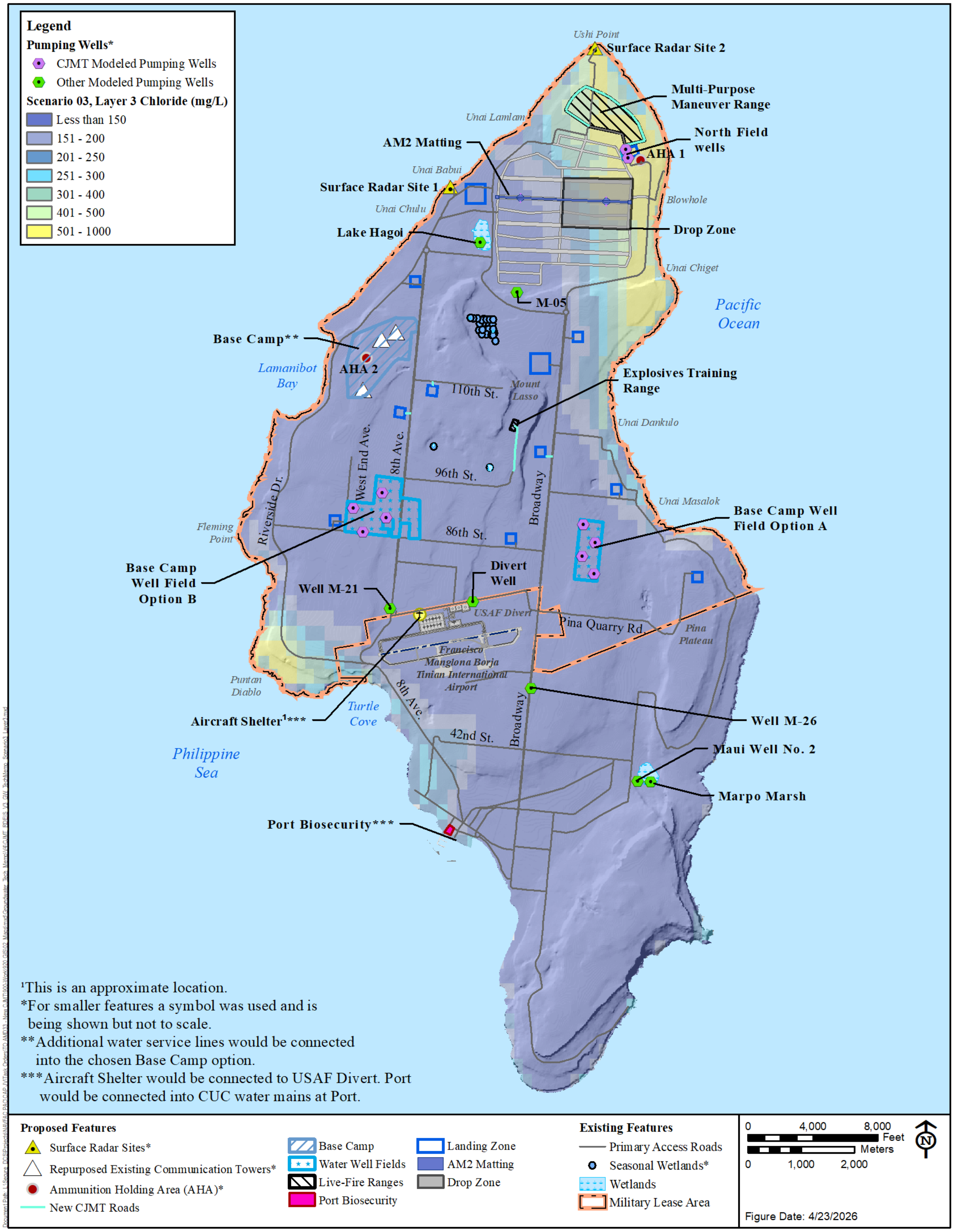


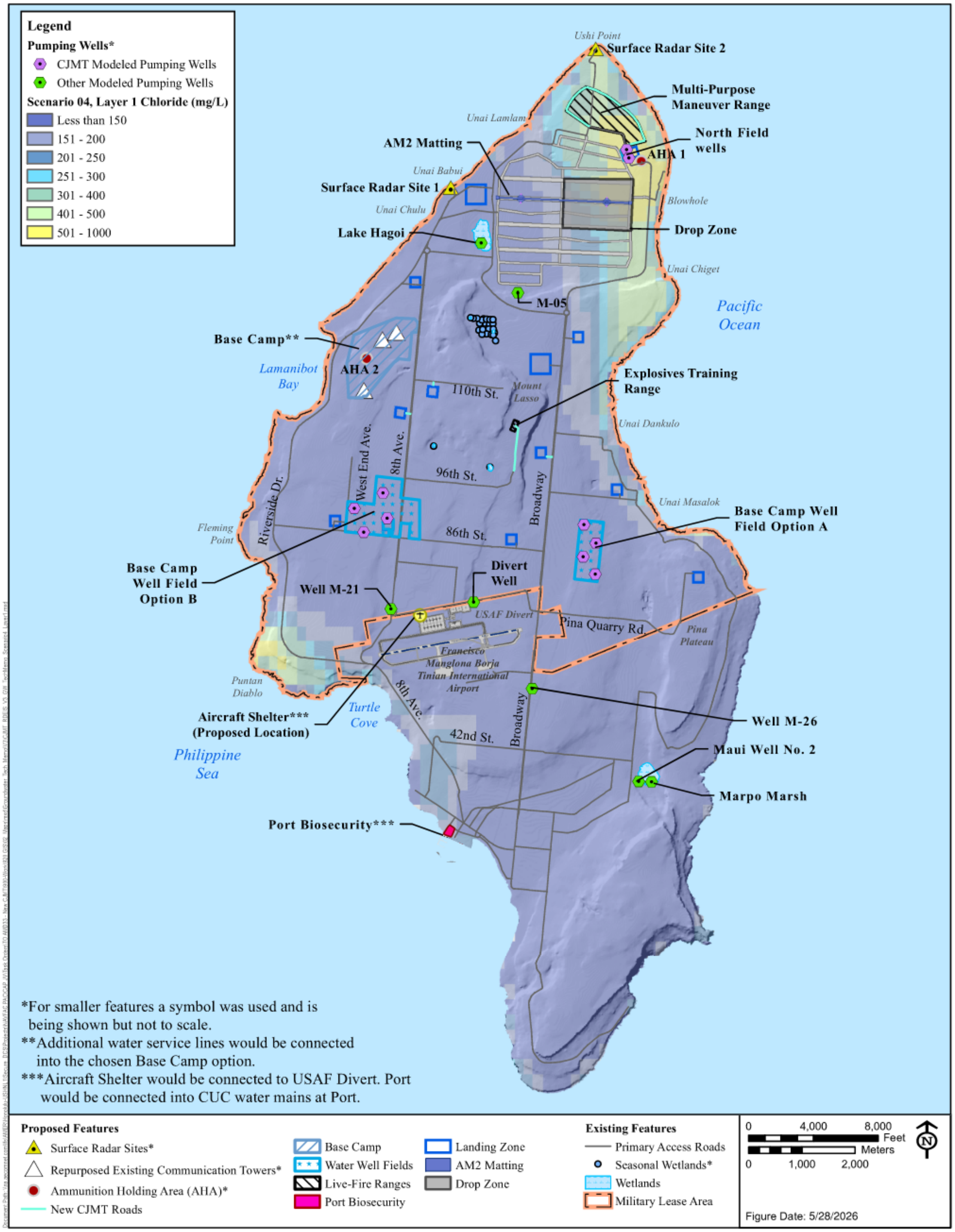
Figure 18.2 Modeled Chloride Concentrations for Layer 2 – Scenario 3



¹This is an approximate location.
*For smaller features a symbol was used and is being shown but not to scale.
**Additional water service lines would be connected into the chosen Base Camp option.
***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure Date: 4/23/2026

Figure 18.3 Modeled Chloride Concentrations for Layer 3 – Scenario 3



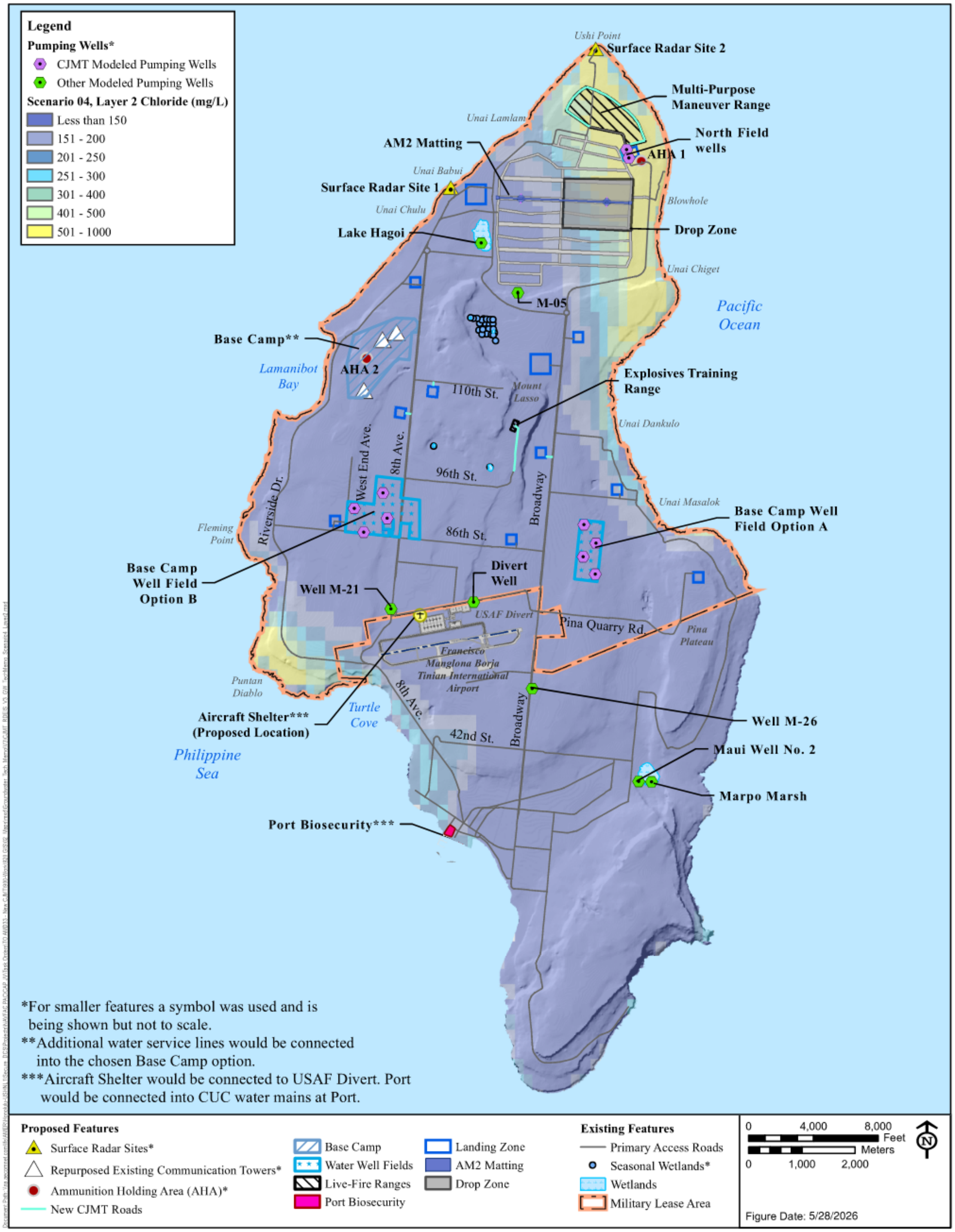
*For smaller features a symbol was used and is being shown but not to scale.

**Additional water service lines would be connected into the chosen Base Camp option.

***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure Date: 5/28/2026

Figure 19.1 Modeled Chloride Concentrations for Layer 1 – Scenario 4



*For smaller features a symbol was used and is being shown but not to scale.
**Additional water service lines would be connected into the chosen Base Camp option.
***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure Date: 5/28/2026

Figure 19.2 Modeled Chloride Concentrations for Layer 2 – Scenario 4

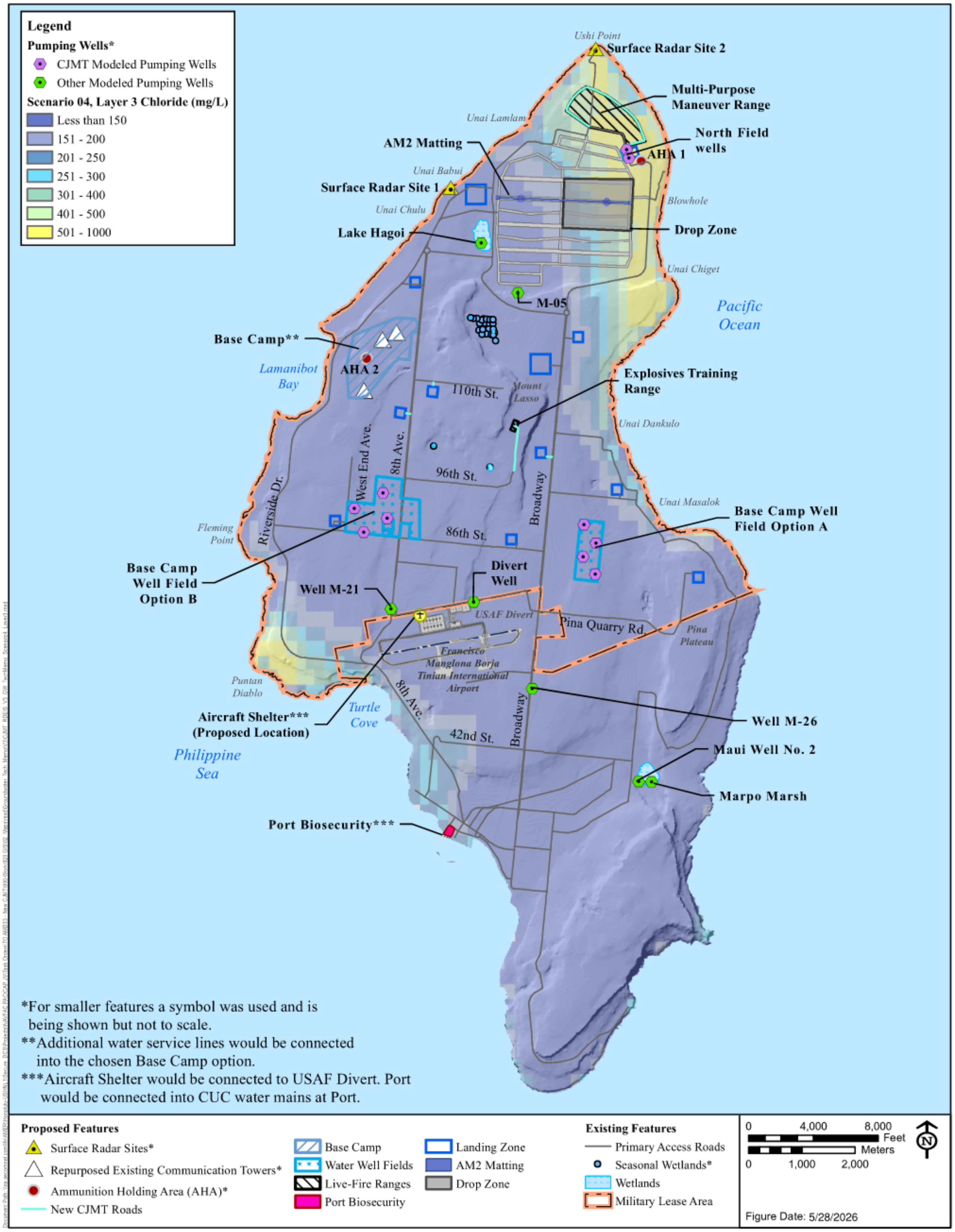
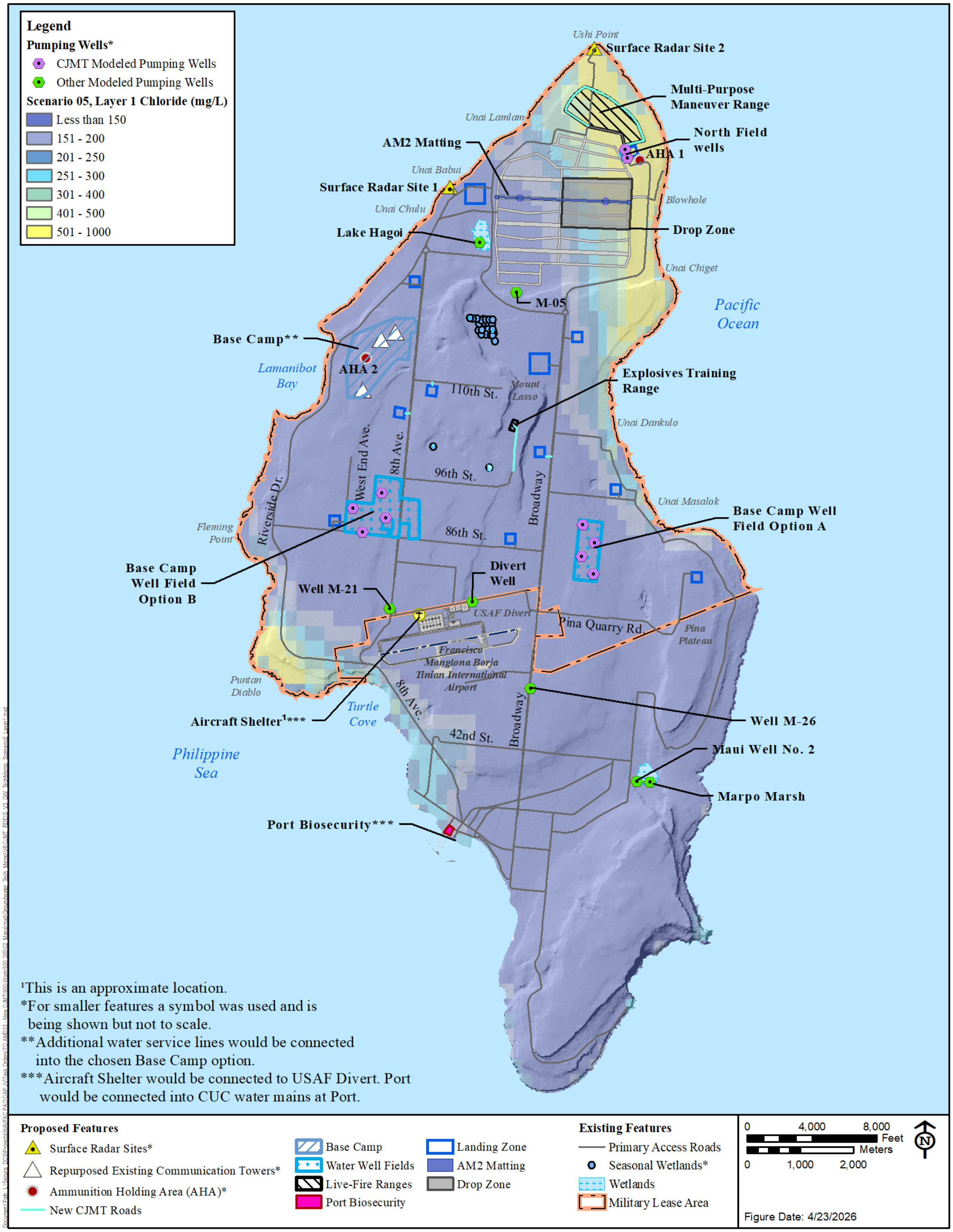
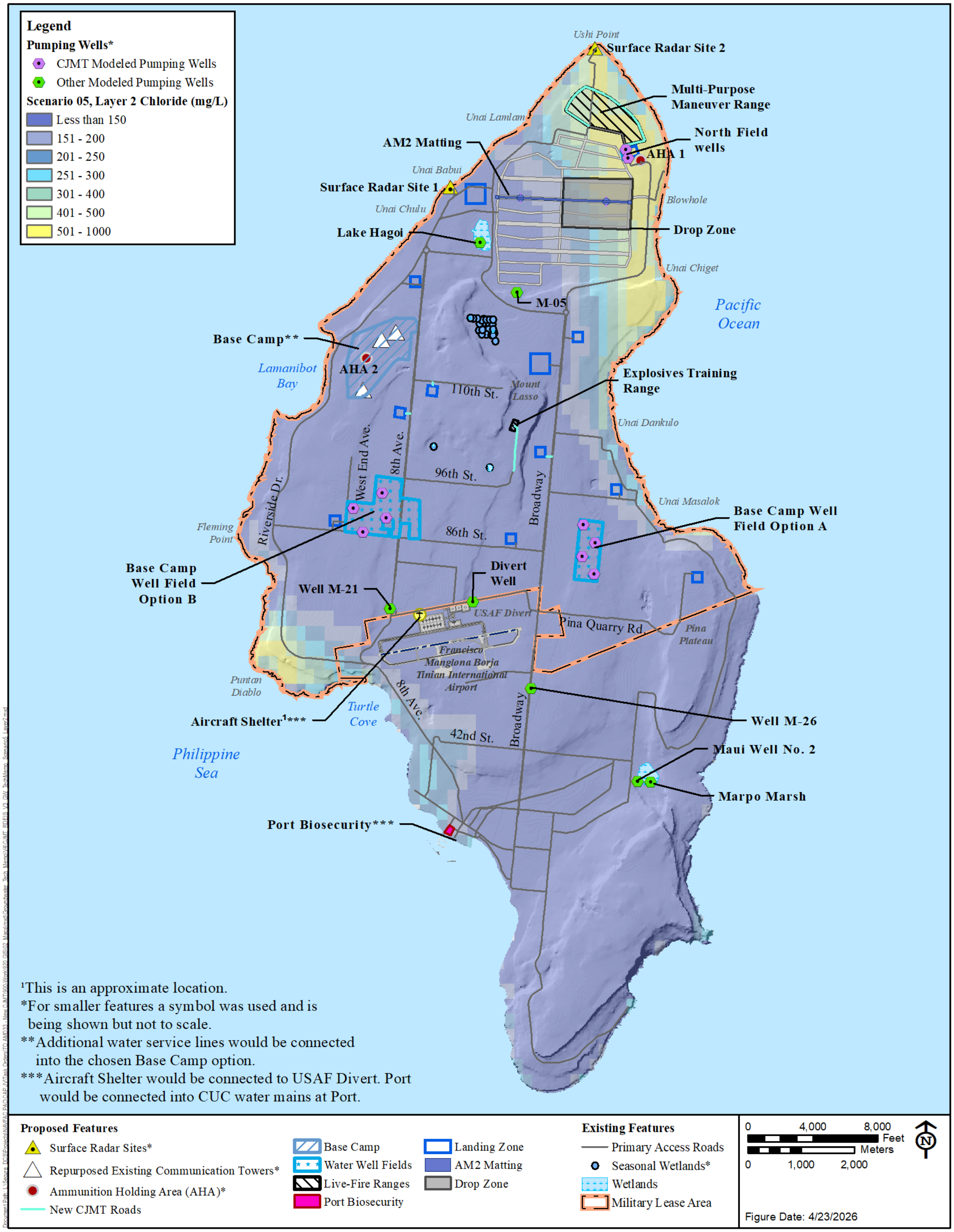


Figure 19.3 Modeled Chloride Concentrations for Layer 3 – Scenario 4



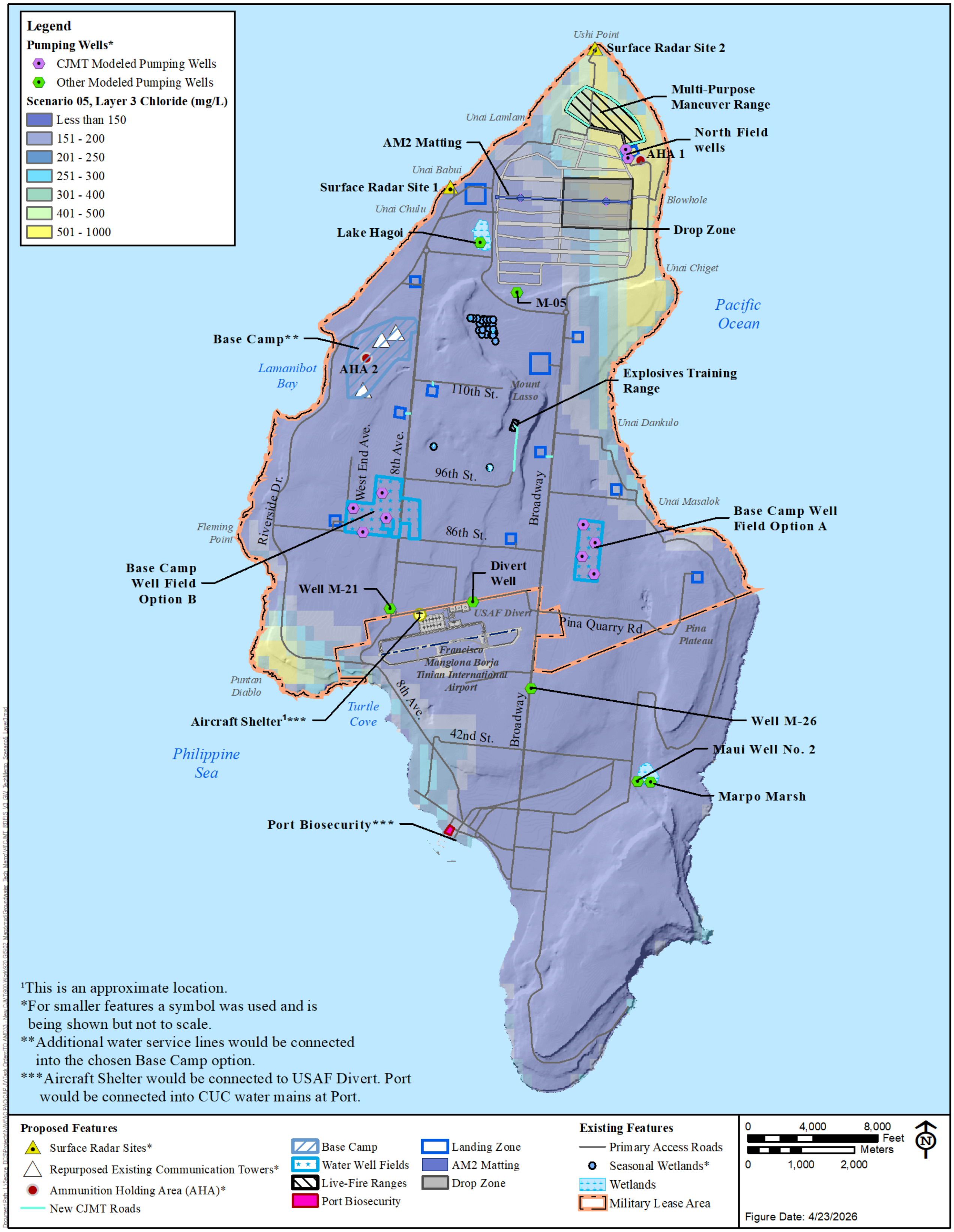
¹This is an approximate location.
*For smaller features a symbol was used and is being shown but not to scale.
**Additional water service lines would be connected into the chosen Base Camp option.
***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure 20.1 Modeled Chloride Concentrations for Layer 1 – Scenario 5



¹This is an approximate location.
*For smaller features a symbol was used and is being shown but not to scale.
**Additional water service lines would be connected into the chosen Base Camp option.
***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure 20.2 Modeled Chloride Concentrations for Layer 2 – Scenario 5



¹This is an approximate location.
*For smaller features a symbol was used and is being shown but not to scale.
**Additional water service lines would be connected into the chosen Base Camp option.
***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure Date: 4/23/2026

Figure 20.3 Modeled Chloride Concentrations for Layer 3 – Scenario 5

¹This is an approximate location.
*For smaller features a symbol was used and is being shown but not to scale.
**Additional water service lines would be connected into the chosen Base Camp option.
***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure 21 Modeled Groundwater Heads and Groundwater Flow Directions – Scenario 1

¹This is an approximate location.
*For smaller features a symbol was used and is being shown but not to scale.
**Additional water service lines would be connected into the chosen Base Camp option.
***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure Date: 4/28/2026

Figure 22 Modeled Groundwater Heads and Groundwater Flow Directions – Scenario 3

¹This is an approximate location.
*For smaller features a symbol was used and is being shown but not to scale.
**Additional water service lines would be connected into the chosen Base Camp option.
***Aircraft Shelter would be connected to USAF Divert. Port would be connected into CUC water mains at Port.

Figure Date: 4/28/2026

Figure 23 Modeled Groundwater Heads and Groundwater Flow Directions – Scenario 5

5.7 EFFECTS OF SEA LEVEL RISE

The scope of work for the study also included the following: "Provide technical basis (hydrogeological) for discussion of sea level rise's potential effects on the availability of freshwater via existing and proposed water wells that may assist planners in strategizing future contingency actions." While the groundwater modeling effort evaluated the short-term impact of drought on chloride concentrations, it did not address long-term changes such as sea level rise. In general, it is expected that sea level rise would result in a concomitant rise in the transition and saltwater zones. This phenomenon would not significantly change the amount of freshwater available especially in areas bounded by sea cliffs. However, a significant rise in sea level could necessitate changes in well screen depths. This could require drilling new wells. It is recommended that periodic groundwater samples be collected from the pumping wells and selected monitoring wells to allow for the assessment of fluctuations of both groundwater elevation and chloride concentration.

5.8 SUSTAINABLE YIELD VS. SUSTAINABLE MANAGEMENT OF AQUIFERS

"Sustainable yield" (also sometimes called "Safe Yield") has traditionally been defined as the rate at which groundwater can be continuously withdrawn from an aquifer without impairing the quality or quantity of the pumped water or the environment. On Tinian, specific yield is not related to groundwater quantity. Overextraction (i.e., unsustainable extraction) could reduce the volume of freshwater and induce drawdown, leading to the replacement of freshwater with saltwater from beneath the transition zone and/or the inward migration of saltwater from the coast. Since saltwater from the ocean is effectively infinite, specific yield is not limited by the aquifer size or groundwater volume in storage, as is often the case in inland continental settings. Instead, the sustainable yield limit on Tinian would be the quantity of usable freshwater available without inducing significant salinity increases within the freshwater aquifer. Before groundwater modeling, and in the absence of a reliable model for a specific aquifer, sustainable yield had generally been estimated as a percentage (typically 20–25 percent) of estimated recharge. However, achieving the hypothetically available sustainable yield would require optimized groundwater withdrawal, which usually does not occur. Optimization would require using many small, shallow wells and/or several Maui-style wells distributed relatively uniformly around the island. Because this approach is not feasible nor proposed on Tinian, the full capacity of the aquifer is generally not available for development. In island aquifers, salinity can rise in proportion to the amount of groundwater extracted and as a percentage of recharge. Recognition of these limitations in the sustainable yield concept, along with the advent of new tools and technologies for aquifer management, such as numerical groundwater modeling, remote monitoring of production and water quality, and variable-rate pumps, has led to its supersession by the "sustainable use" or "sustainable management" concept (Alley and Leake 2004).

Reliable models provide useful tools for general estimates of the trade-offs between extraction and water quality. For any given well or well field, however, the most effective management practice involves frequent measurement and tracking of the relationship among water quality, extraction, and recharge, with appropriate adjustments of production as indicated by the data. Therefore, it is crucial for managers to obtain baseline and ongoing data on water quality and well performance.

For the proposed CJMT Base Camp and North Field wells, it is important to maintain running records of water quality, correlated with pumping rates and monthly and annual rainfall. Well fields and individual wells should be constructed so that managers, working with hydrogeologists familiar with the local climate and aquifer properties, can adjust or redistribute the production rates among wells as trends in performance and water quality evolve. Water production, water level and water quality data must be submitted to the CNMI Bureau of Environmental and Coastal Quality upon initial well permitting and annually during re-permitting for operation. Based on that data, Bureau of Environmental and Coastal Quality assigns maximum extraction rates on a well-by-well basis.

The U.S. Geological Survey estimated Tinian’s average annual groundwater recharge to be about 30 inches per year, using the bookkeeping method with daily rainfall data from 1987 to 1997 (U.S. Geological Survey 2002). This recharge rate represents approximately 37 percent of the total rainfall and equals to approximately 62,000 acre-feet per year or 55 million gallons per day. Doan et al. (1960) stated there were two air bases and one naval base on the island with a maximum total population of about 250,000 personnel near the end of World War II, and groundwater resources “were adequate” to supply this entire population. Demand at the time was estimated to be approximately 2.3 million gallons per day, which was not thought to be the “maximum exploitable yield.” The existing wells at that time provided a maximum supply of 2.5 million gallons per day. It was estimated that a more “ambitious” extraction program (i.e., with additional wells) could yield 3 to 4 million gallons per day. Doan et al. (1960) also referenced a study from Piper (1946) that reported a maximum production of 12 million gallons per day at some unstated date. If this production occurred during World War II, it would represent 48 gallons per person per day with 250,000 personnel on island. No additional information about this report could be found.

The current island demand (including evaporation and evapotranspiration losses) is estimated at approximately 1.1 MGD. Total groundwater consumption, combining civilian use and DoD operations (CJMT, Divert and North Field wells), is estimated at approximately 1.3 MGD. That value represents about 2 percent of the estimated recharge, which is significantly below the theoretical maximum sustainable yield of 20 to 25 percent of recharge mentioned earlier and substantially lower than the 2.3 MGD or 12 MGD reported by Doan et al. (1960) and Piper (1946).

5.9 MODEL LIMITATIONS AND UNCERTAINTIES

A groundwater model is a simplification of the natural environment and inherently has limitations. Consequently, some degree of uncertainty exists in any numerical model’s ability to fully predict groundwater flow and contaminant transport. Model output uncertainty arises from uncertainties in the conceptual model, input parameters, and the numerical model’s ability to replicate field conditions.

To minimize uncertainty, AECOM used real-world data whenever available and conducted extensive model simulations for calibration. Where data were limited, conservative values were applied to high-uncertainty parameters. Despite these efforts, no warranty, expressed or implied, guarantees that this study accounts for all hydrogeological, hydrological, environmental, or other site-specific characteristics.

The groundwater model developed for this project provides a detailed representation of the subsurface hydrogeology of the island and an extended area beyond the island boundaries. This broader coverage minimizes boundary effects on model results. However, like all numerical models, it has inherent limitations and uncertainties due to data availability, assumptions, and necessary simplifications.

The 2025 AECOM model assumed equivalent porous media. The Tinian aquifer is recognized as a triple-porosity Carbonate Island Karst aquifer where fracture and conduit porosity may be present. Further, the precise locations and hydraulic properties of these features are nearly impossible to document comprehensively in the field and cannot be fully incorporated into current modeling codes, including those used in this study. As a result, salinity responses of individual wells to pumping and contaminant migrations from specific locations may show significant local deviations from the model's prediction. Table 11 summarizes factors that could influence the modeling results and their potential impacts on the results.

Table 11. Model Limitations

Model Limitations	*Potential Impact on Model*
Lack of Detailed Aquifer Data.	a) There are no field test data for specific yield for the limestone (Tagpochau Limestone and/or Mariana Limestone) or volcanic rocks (Tinian Pyroclastic Rock). There was no mention of response to pumping in unpumped observation wells. b) For hydraulic conductivity, there is significant variability (21 feet per day to 23,000 feet per day) in the data from the limestone units and only one pump test in volcanic rocks. c) There are few temporal chloride concentrations. Only one well (Maui Well Number 2) has temporal or recent chloride data. d) There is limited information on spatial distribution of rainfall recharge.
Insufficient Calibration Data: Head and chloride concentration data are spatially and temporally inadequate for calibration.	Limit the model's ability to be well-calibrated, thus reduce reduces confidence in model predictions.
Non-uniqueness Representation of Rock Distribution: Variability in rock extent and distribution introduces uncertainty.	Introduces uncertainty in aquifer properties and model results. Different plausible geologic interpretations yield different hydraulic properties and flow conditions, affecting predicted groundwater movement and solute transport.
Coarse Model Grid: The model grid is relatively coarse, leading to lateral discontinuity in cells that violate the 50% rule of thumb.	Coarse grid may lead to inaccuracies in representing hydrogeologic features (especially near sharp boundaries or abrupt lithologic changes). Lateral discontinuities in cell properties may violate the 50% rule of thumb, potentially distorting hydraulic gradients and solute.
Averaged Chloride Concentrations: Modeled chloride concentrations represent cell-wide averages, which may be too coarse to accurately track specific isochlor (e.g., the 250 mg/L contour).	Localized concentration variations may not be captured. This can lead to smoothed concentration distributions that may not accurately depict isochlors, such as the 250 mg/L contour, affecting the assessment of salinity intrusion.

Model Limitations	*Potential Impact on Model*
Simplified Geological Representation: Geologic features are modeled at a coarse resolution, potentially affecting hydrologic behavior and model accuracy.	May lead to over-simplifications in key hydrostratigraphic features, potentially affect the accuracy of simulated flow paths, aquifer connectivity, leading to inaccurate interpretation of groundwater movement and solute transport.
Conservative Chloride Assumptions: Background and recharge chloride concentrations are likely conservative.	Model results may overestimate chloride impacts, leading to potentially pessimistic projections of salinity intrusion or water quality degradation. While this approach may provide a protective estimate, it could also lead to overly restrictive management decisions.

Legend: % = percent; mg/L = milligram per liter.

As with any groundwater model used to make predictions, achieving more definitive results requires periodically revisiting the model as new data become available and comparing projections with observed conditions. This model in particular was constructed with numerous assumptions due to limited data availability and would benefit from additional data collection. Despite these issues the model results are useful for the purposes intended.

The 2002 USGS model was used as a starting point for developing a 3-D flow and transport model. Combined with the *Aquifer Study Technical Memorandum* (DON 2015) and the more recent Maui Well No. 2 data, this model is considered adequate for environmental evaluation purposes. However, spatial and temporal variation/fluctuation should be anticipated as it is not possible to capture all geologic heterogeneity in a numerical representation of the natural system.

The current model provides conservative projections because where data were limited or unavailable, conservative values were applied to high-uncertainty parameters. For example, relatively low specific yield (or effective porosity) of 28 percent was used in the model, although "the higher values of porosity (30 to 50 percent) seem more likely to be representative of actual aquifer properties (USGS 2002)." The use of a lower specific yield would result in less groundwater in storage, higher groundwater velocities and a shallower freshwater/saltwater interface.

5.10 MODEL SUMMARY

Based on the modeling described herein, the following conclusions are made:

- The Proposed Action (Scenario 2 or 4) is not predicted to increase chloride concentrations at Maui Well No. 2 from 2016 conditions. Under drought conditions (Scenario 3 or 5), the chloride concentration is expected to rise temporarily by less than 20 milligrams per liter and would still meet the secondary maximum concentration level. While the average chloride concentration is not expected to exceed the secondary maximum concentration level on average, seasonal variations in precipitation and pumping, along with analytical variability, could occasionally result in exceedances.
- Under all scenarios, water quality at the proposed Base Camp wells at either Well Field A or Well Field B is expected to meet the secondary chloride maximum concentration level.
- Although the secondary drinking water maximum concentration level does not strictly apply to agricultural, firefighting, or construction wells, the modeling indicates the chloride concentrations at M-21, M-26, M-05, and the Divert well would remain below this

threshold under all scenarios. However, chloride concentrations at the two North Field wells would exceed these standards under normal rainfall and drought conditions.

- The proposed CJMT pumping at either Base Camp well field option plus the new North Field wells is expected to have a less than significant impact on island potable groundwater quality.

This study supports the determination that the Proposed Action would not result in significant impacts to groundwater (short- and long-term availability of water and groundwater quality). Improving the overall resilience of Tinian's aquifer, conducting long term monitoring of the aquifer at large, development of emergency response actions and contingency plans, and assessing the potential vulnerability of the community drinking water system were outside of the scope of this study.

The groundwater model evaluated both drought and normal rainfall scenarios. The model used existing and reasonably foreseeable water demands including Commonwealth Utilities Corporation potable water demand, agricultural demands, U.S. Air Force construction and operational demands, U.S. Air Force operational demands, and USMC construction and operational demands, and USMC operational demands. This analysis conservatively assumed a continuation of construction demands long-term that would actually only be temporary and intermittent.

6 WELL SITING, INSTALLATION AND OPERATION RECOMMENDATIONS

6.1 RECOMMENDATIONS

The USMC will continue to coordinate with the CNMI Bureau of Environmental and Coastal Quality on specific details such as permitting and the locations of wells. Annual CNMI Bureau of Environmental and Coastal Quality permitting requirements include reporting pumping volumes and water quality on a well-by-well basis. Based on this information, the Bureau of Environmental and Coastal Quality determines annually the allowable pumping volume for the following year.

At the request of CNMI, the DoD would fund a one-time hydrogeological study to establish baseline data that could be used to support monitoring of Tinian's aquifer. This study would consist of groundwater sampling at existing well locations, and laboratory testing of water samples. In addition, the DoD would install up to four groundwater monitoring wells at each of the two live-fire ranges, establish a water monitoring plan, and include one year of baseline monitoring before ranges would become operational. The locations of wells would be determined in collaboration with CNMI Bureau of Environmental Quality.

Based on a total borehole depths of approximately 17 feet below msl and completed well screens from roughly msl to 15 feet below msl, it is anticipated that the CJMT wells shown in Figure 4 would provide water that complies with the EPA and CNMI drinking water regulations. These include permits and annual reporting required by Bureau of Environmental and Coastal Quality (Division of Environmental Quality 2005). The practical thickness of the freshwater lens (i.e., depth within which chloride is less than the secondary maximum concentration level of 250 milligrams per liter) is generally much thinner than the theoretical 50% isochlor (chloride concentration equal to approximately 9,700 milligrams per liter). The freshwater lens thickness can also vary seasonally and with change in annual rainfall. Past practice elsewhere on the Mariana Islands has been to screen or leave open wells from the water table down to 40–50 feet below mean sea level. However, accumulated experience with drilling and well development elsewhere on the Mariana Islands (Camp, Dresser and McKee, Inc. 1982), along with more recent developments (Gulley et al. 2012), suggest that most of the production in productive wells comes from the first 15–20 feet below mean sea level due to the preferential development of phreatic caves near the freshwater table. Prospects for saltwater contamination could be reduced by limiting well completion depths. Consistent with the sustainable management concept in the *Aquifer Study Technical Memorandum* (DON 2015), increasing the number of wells, setting them at shallower depths, and operating them at more modest rates than traditionally sought would enhance the water quality while achieving overall production goals.

Based on the specific capacities from the pump tests cited in the *Aquifer Study Technical Memorandum* (DON 2015), it is expected that drawdown associated with pumping approximately 60 gallons per minute could range from about 0.1 to 19 feet. To maintain well performance and water quality, drawdown should not be allowed to exceed approximately 0.5 foot. Therefore, boreholes should be pump tested to confirm adequate specific capacity prior to well completion. Significant seawater intrusion (lateral migration and/or upconing) is not expected to cause dissolved solids and chloride if well screens are set no deeper than 15 feet below msl and pumping rates are limited to produce no more than the drawdown listed above. However, this should be monitored frequently throughout the life of each well, and wells should be constructed with adjustable pumping capabilities to optimize both production and water quality. Given the characteristics of this aquifer, water quality from wells is likely to respond rapidly to changes in pumping rates. Even with conscientious management, occasional increases in salinity may occur in individual wells, particularly during extended dry periods or long-term sea level fluctuations. In such cases, reduced pumping or replacing the affected well may be necessary to maintain water quality.

The CJMT wells should draw water primarily from the Tagpochau Limestone and the Mariana Limestone. Because the limestone may be thinner in some areas (i.e., the basement rock is shallower), lithologic and geophysical logging should be performed at each pilot hole to confirm adequate limestone thickness. Locations outside of well fields A or B were not evaluated. Additional recommendations for well siting, setbacks, installation, testing, and operation are provided in the *Aquifer Study Technical Memorandum* (DON 2015).

6.2 WELL SITING AND INSTALLATION

Prior to finalizing location of any of the exploratory wells at candidate sites the following should be performed:

- Review of the following figures from the *Aquifer Study Technical Memorandum* (DON 2015): Figure 5.7-1 (Analytical Results on Gingerich and Yeatts 2000 Groundwater Levels), Figure 5.7-2 (Hydraulic Head and Groundwater Flow Direction), Figure 5.7-3 (Surface Geology and Proposed Well Network), Figure 5.7-4 (Topography, Hydrology and Depressions on U.S. Navy 2010 Aerial Photo), and Figure 6.1-1 (Proposed Wells on Doan and Other, 1960 Groundwater Resources Map).
- Site reconnaissance before and after vegetation clearing to find any surface debris, tanks, piping, soil discoloration, or collapse features.
- Unexploded ordnance, munitions and explosives of concern, and utility clearance.
- Mapping of any surface geologic exposures collapse features or manmade features.
- Any future wells should be sited within the well fields A or B shown in Figure 4. The wells would be located outside of proposed training constraints, proposed water disposal/infiltration features, biological constraints, cultural constraints, hazardous waste/hazardous materials constraints, fractures, joints, faults, and karst features.
- Step testing and constant-rate pump testing of pilot holes and completed wells. Pilot borings with expected drawdown of 2 feet or more and/or a specific capacity of less than 30 gallons per minute per foot of drawdown should not be completed. Such holes could be considered for monitoring wells by which to observe changes in water levels and quality.
- Water quality testing of a whole water sample collected near the end of pump testing for all Safe Drinking Water Act analytes.
- Periodic samples should also be collected during pilot-hole and completed-well step- and constant-rate pump testing and analyzed in accordance with the CNMI *Well Drilling and Well Operation Regulations* (Department of Environmental Quality 2005). Hourly samples

should be collected throughout the pumping phase for chloride analysis. Transducers that record water level and specific conductivity should be used to augment hourly samples.

- Video-logging of new boreholes and completed wells. Logging of new holes, and archiving of the video, would provide a basis for the hydrogeologist(s) to make informed predictions and diagnoses of well performance, as well as subsequent mitigation decisions regarding causes and appropriate responses to changes in salinity.
- Well field and well design include the following considerations: Wells should be spaced no closer than allowed by the setbacks by Bureau of Environmental and Coastal Quality, and wells should not be placed any closer than 500 feet from each other or karst collapse features.
- Minimum 12-inch-diameter pilot holes should be drilled to no more than 17 feet below sea level.
- Pilot holes should be geologically logged based on cuttings and geophysically logged using tools (i.e., spontaneous potential, resistivity, gamma, guard resistivity, acoustic [sonic] log) to include character of limestone and evidence of faults, joints, fractures, and solution cavities. Tools should selected and positioned to optimize geophysical signals.
- The well screens should extend from sea level to a nominal depth of 15 feet below mean sea level.
- Following geophysical logging, the pilot hole should be reamed to a minimum 18-inch diameter. A caliper log should be performed of the reamed borehole (if the caliper survey shows the hole to be less than the specified diameter at any point, the hole should be re-reamed and resurveyed).
- Completed well borings should be at least 18 inches in diameter.
- Wells should be constructed of 12-inchdiameter, 5/16-inch thick, high-strength, low-alloy casing (ground surface down to 20 feet above mean sea level) and 304L stainless steel casing (20 feet above mean sea level down to mean sea level) connected with a di-electric coupler approximately 20 feet above mean sea level and 12-inchdiameter, 5/16-inch 304L, stainless steel Roscoe Moss Ful Flo screen, and a 2-foot long by 18 5/16-inch stainless steel casing well sump.
- Screen aperture and filter pack/formation stabilizer gradation should be designed by the hydrogeologist and engineer designing the wells.
- The casing should be round, straight, and plumb. The deviation of the casing is measured from a plumb vertical line centered at the top of the inner casing and is calculated as the actual deviation of the well casing from this centerline at the depth of the caging tool. Testing should be conducted to verify the plumbness and alignment of the casing. The completed well should be drilled in such vertical alignment that a line drawn from the center of the well casing at ground surface to the center of the well casing at the bottom depth below ground surface should not deviate from the vertical more than 2/3 of the inside diameter of the well casing per 100 feet of depth (American Water Works Association A100). Two plots of plumbness and alignment of the completed well should be completed in planes oriented at 90 degrees with respect to each other.
- The design flow rate should be no more than 60 gallons per minute per well. To reduce the risk of pump cavitation, provide adequate pump cooling, and accommodate seasonal and decadal ocean water elevation changes, the pump intake should be placed a nominal 14 feet

below mean sea level. Well pumping rates should be modulated to prevent drawdown greater than 0.5 feet in each well.

- It is also assumed that Bureau of Environmental and Coastal Quality would require monitoring wells associated with the new production wells as described in the CNMI *Well Drilling and Well Operations Regulations* (Department of Environmental Quality 2005). Although the final numbers and locations cannot be determined before consultation with Bureau of Environmental and Coastal Quality and possibly additional investigation for planning purposes, it is recommended that at least one deep monitoring well (through the transition zone) at the new CJMT well field be installed to allow profiling of the salinity and tracking of its response to changes in well pumping, rainfall recharge, and ocean water levels.
- Any wells or boreholes not to be used as production or monitoring wells should be properly abandoned under the direction of Bureau of Environmental and Coastal Quality.
- Production wells should include a 3-inch diameter gravel feed tube and 2-inch diameter sounding tube. The filter pack/formation stabilizer and transition sand should be installed. The filter pack/formation stabilizer should be installed a minimum of 15 feet above the top of the screen interval.
- The filter pack/formation stabilizer should be placed by pumping through a tremie pipe extending to the bottom of the casing hole annulus. The tremie pipe should be gradually withdrawn as the filter pack/formation stabilizer is placed. Swabbing and circulating should be continued during placement of the filter pack/formation stabilizer.
- After the filter pack/formation stabilizer has been swabbed into place to the proper depth, the transition sand should be installed a minimum of 10 feet above the top of the filter pack/formation stabilizer.
- The filter pack/formation stabilizer should be disinfected with chlorine during placement as per specifications. The completed well, pumping equipment, and piping should be disinfected in accordance with the CNMI *Well Drilling and Well Operation Regulations* (Department of Environmental Quality 2005).
- After the transition sand is installed, the annular space between the borehole and the well casing should then be filled with cement grout from the top of the filter pack/formation stabilizer to 18 inches below the ground surface.
- A total of 48 hours after the installation of cement-bentonite grout, the well should be carefully swabbed to properly settle the sand pack.
- The completed well should be developed by surge-block-and-air-lift method for a minimum of 6 hours.
- The completed well should be video-logged from top to bottom to document well conditions.
- A submersible or line-shaft turbine test pump should be installed.
- An 8-hour step test should be performed with steps at 50 percent, 75 percent, 100 percent, and 125 percent of design capacity.
- Following review of drilling logs, geophysical logs, video log, and step test data, a 48-hour constant rate test should be performed at a rate determined from the step test.

7 MODELING TEAM

The groundwater team members and team roles are listed below:

- **Groundwater Team Leader.** Doug Roff, PG, CEG, CHg.
- **Modeling Team.** Jim Zhang, PhD, PE (lead); Bianca Mintz, PG, CHg; Doug Roff, PG, CEG, CHg.
- **Geology/Hydrogeology Team.** Doug Roff, PG, CEG, CHg**;** Bianca Mintz, PG, CHg
- **Reviewer.** Joe Harrigan, PG.

8 REFERENCES

Alley, W.M. and Leake, S.A. 2004. The Journey from Safe Yield to Sustainability. *Groundwater*. 42: 12-16. https://doi.org/10.1111/j.1745-6584.2004.tb02446.x

Aquaveo. 2021. *GMS - Groundwater Modeling System v10.8*. https://www.aquaveo.com/software/gms-groundwater-modeling-system-introduction

American Society for Testing and Materials. 2010a. *Standard Guide for Application of a Groundwater Model to a Site-Specific Problem.* ASTM D5447−04.

American Society for Testing and Materials. 2010b. *Standard Guide for Selecting a Groundwater Modeling Code.* ASTM D6170-17.

Allied Pacific Environmental Consulting (APEC). 2025. *Constant-Rate Pumping Test Report, Tinian North Field, CNMI – Ushi & M-10 Wells*. December.

Baydon-Ghyben, W. 1888–1889. *Nota in Verband Met de Voorgenomen Putboring Nabij Amsterdam*. Koninklyk Institute Ingenieurs Tijdschrift. Pages 8–22.

Camp, Dresser and McKee, Inc. 1982. *Northern Guam Lens Study, Groundwater Management Program, Aquifer Yield Report.* Prepared by Camp, Dresser and McKee, Inc. in association with Barrett, Harris & Associates for Guam Environmental Protection Agency.

Commonwealth Utilities Corporation. 2013. “Commonwealth Utilities Corporation 2012 Water Quality Report.” *Commonwealth Utility News.* July 1.

Commonwealth Utilities Corporation. (2014). “2013 Water Quality Report.” *Commonwealth Utility News*. July.

Commonwealth Utilities Corporation. (2015). “2014 Water Quality Report.” June.

Commonwealth Utilities Corporation. (2016). “2015 Water Quality Report.” *Commonwealth Utility News*. July.

Commonwealth Utilities Corporation. (2017). “2016 Water Quality Report.” *Commonwealth Utility News*. July.

Commonwealth Utilities Corporation. (2018). “2017 Tinian Water Quality Report.” *Commonwealth Utility News*. July.

Commonwealth Utilities Corporation. (2019). “2018 Tinian Water Quality Report.” *Commonwealth Utility News*. July.

Commonwealth Utilities Corporation. (2020). “2019 Tinian Water Quality Report.” *Commonwealth Utility News*. July.

Commonwealth Utilities Corporation. (2021). “2020 Tinian Water Quality Report.” *Commonwealth Utility News*. July.

Commonwealth Utilities Corporation. (2022). “2021 Tinian Water Quality Report.” *Commonwealth Utility News*. July.

Commonwealth Utilities Corporation. (2023). “2022 Tinian Water Quality Report.” *Commonwealth Utility News*. July.

Commonwealth Utilities Corporation. (2024). “2023 Tinian Water Quality Report.” *Commonwealth Utility News*. July.

Department of Environmental Quality. 2005. *Well Drilling and Well Operation Regulations.* Office of the Governor. September.

Doan, D. B., H. W. Burke, H. G. May, and C. H. Stensland. 1960. *Military Geology of Tinian, Mariana Islands*. Prepared under the direction of the Chief of Engineers, U.S. Army by the Intelligence Division, Office of the Engineer Headquarters, United States Army Pacific with personnel of the United States Geological Survey. Available at: http://search.library.cornell.edu/catalog/5099117.

DON. 2015. *Final (Version 3) Commonwealth of the Northern Mariana Islands Joint Military Training Aquifer Study Technical Memorandum.* JBPHH, HI: Prepared for NAVFAC Pacific. November.

DON. 2025. *Potable Water Study Update V2a3 in Support of the Commonwealth of the Northern Mariana Islands Joint Military Training Environmental Impact.* JBPHH, HI: Prepared for NAVFAC Pacific. April.

EMRL. 2005. Groundwater Modeling System (GMS). Environmental Modeling and Research Laboratory. Brigham Young University. Version 6.0.

Essaid, H. I. 1990. *The Computer Model SHARP, a Quasi-Three-Dimensional Finite-DIFFERENCE model to Simulate Freshwater and Saltwater Flow in Layered Coastal Aquifer Systems*. U.S. Geological Survey, Water-Resources Investigations Report 90-4130.

Gulley, J. D., J. B. Martin, P. J. Moore, and J. Murphy. 2012. *Formation of Phreatic Caves in an Eogenetic Karst Aquifer by CO_2 Enrichment at Lower Water Tables and Subsequent Flooding by Sea Level Rise: Earth Surface Processes and Landforms*. DOI: 10.1002/esp.3358.

Herzberg, A. 1901. “Die Wasserversorgung Einiger Nordseebader.*” Journal Gasbeleuchtung und Wasservesorgung* 44:815–819, 842–844.

Hill, M.C., E.R. Banta, A.W. Harbaugh, and E.R. Anderman. 2000. MODFLOW 2000. “The U.S. Geological Survey Modular Ground-Water Model; User Guide to the Observation, Sensitivity, and Parameter-Estimation Processes and Three Post-Processing Programs.” Open-File Report 00 184. U.S. Geological Survey. Denver Colorado.

Jenson, J. W., T. M. Keel, J. R. Mylroie, J. E. Mylroie, K. W. Stafford, D. Taborosi, and C. Wexel. 2006. “Karst of the Mariana Islands: The Interaction of Tectonics, Glacio-Eustasy, Fresh-Water/Salt-Water Mixing in Island Carbonates.” *Geological Society of America Special Papers* 404:129–138.

Lawlor, J.P. 1946. *Skimming trench solves a coral island water supply problem: Engineering News-Record*, v. 137, p. 993-995.

McDonald, M.G., and A.W. Harbaugh. 1988. “A Modular Three-Dimensional Finite-Difference Ground-water Flow Model.” Book 6, Chapter A1. *Techniques of Water-Resources Investigations of the United States Geological Survey.* USGS. Reston, Virginia.

National Oceanic and Atmospheric Administration (NOAA), National Integrated Drought Information System (NIDIS), and partners. 2025. *Pacific Region Climate Impacts and Outlooks: Fall 2025.* Prepared by Simeral, David, in cooperation with NOAA Climate Prediction Center and affiliated Pacific regional partners. Available at: https://www.drought.gov/sites/default/files/2025-12/Pacific%20Fall%202025.pdf

Rotzoll, K., S. B. Gingerich, J. W. Jenson, and A. I. El-Kadi. 2013. "Estimating Hydraulic Properties from Tidal Attenuation in the Northern Guam Lens Aquifer, Territory of Guam, USA." *Hydrogeology Journal* 21(3):643–654.

Stafford, K. W., J. E. Mylroie, and J. W. Jenson. 2004. *Karst Geology of Aguijan and Tinian: CNMI Cave Inventory and Structural Analysis of Development.* WERI Technical Report No. 106.

Stafford, K. W., J. E. Mylroie, D. Taboroši, J. W. Jenson, and J. R. Mylroie. 2005. "Karst Development on Tinian, Commonwealth of the Northern Mariana Islands: Controls on Dissolution in Relation to the Carbonate Island Karst Model." *Journal of Cave and Karst Studies* 67(1):14–27.

Tetra Tech. 2012. *Geotechnical Design Report for the Tinian Landfill, Tinian, MP.* Tamuning, Guam. Prepared for Commonwealth of the Northern Mariana Islands Capital Improvement Program Office/Office of the Governor, Saipan, MP. February.

United States Department of Agriculture, Soil Conservation Service (USDA SCS). 1989. *Soil Survey of the Islands of Aguijan, Rota, Saipan, and Tinian, Commonwealth of the Northern Mariana Islands.* Prepared by Young, Fred, in cooperation with the Commonwealth of the Northern Mariana Islands.

U.S. Geological Survey. 1999. *Topographic Map of the Island of Tinian, Commonwealth of the Northern Mariana Islands.* Available at: http://mappery.com/map-of/Tinian-island-topo-Map.

U.S. Geological Survey. 2000. *Ground-Water Resources of Tinian, Commonwealth of the Northern Mariana Islands* (No. 00-4068). U.S. Geological Survey Water-Resources Investigations Report 00-4068. Prepared by Gingerich, S. B., and D. S. Yeatts. Prepared in cooperation with the Commonwealth Utilities Corporation, Commonwealth of the Northern Mariana Islands. Available at: http://pubs.usgs.gov/wri/2000/4068/.

U.S. Geological Survey. 2002. *Geohydrology and Numerical Simulation of Alternative Pumping Distributions and the Effects of Drought on the Ground-Water Flow System of Tinian, Commonwealth of the Northern Mariana Islands.* U.S. Geological Survey Water-Resources Investigations Report 02-4077. Prepared by Gingerich, S. B. Prepared in cooperation with the Commonwealth Utilities Corporation, Commonwealth of the Northern Mariana Islands.

U.S. Geological Survey. 2008. *SEAWAT Version 4: A Computer Program for Simulation of Multi-Species Solute and Heat Transport.* U.S. Geological Survey Techniques and Methods Book 6, Chapter A22. Prepared by Langevin, C.D., Thorne, D.T., Jr., Dausman, A.M., Sukop, M.C., and G. Weixing.

U.S. Geological Survey. 2013. *The Effects of Withdrawals and Drought on Groundwater Availability in the Northern Guam Lens Aquifer, Guam*. U.S. Geological Survey Scientific Investigations Report 2013-5216. Prepared by Gingerich, S. B. Prepared in cooperation with Headquarters, United States Marine Corps.

Wang, H.F. and M.P. Anderson. 1982. *Introduction to Groundwater Modeling: Finite Difference and Finite Element Methods.* San Diego, CA: Academic Press, Inc., A Division of Harcourt Brace & Company.

Vann, D. T., V. M. Bendixson, D. F. Roff, N. C. Habana, C. A. Simard, R. M. Schumann, and J. W. Jenson. 2013. *Topography of the Basement Rock beneath the Northern Guam Lens Aquifer and Its Implications for Groundwater Exploration and Development.* Technical Report #142. Water & Environmental Research Institute of the Western Pacific, University of Guam.

Zheng, C. 1990. *MT3D, A Modular Three-Dimensional Transport Model for Simulation of Advection, Dispersion and Chemical Reactions of Contaminants in Groundwater Systems.* Report to the U.S. Environmental Protection Agency. Robert S. Kerr Environmental Research Laboratory. Ada, Oklahoma. October.

Zheng, C. and P.P. Wang. 1999. *MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion and Chemical Reactions of Contaminants in Groundwater Systems (Release DoD_3.50.A) Documentation and User's Guide.* U.S. Army Corps of Engineers. Contract Report SERDP-99. Tuscaloosa, AL: University of Alabama.

ATTACHMENT A
KNOWN CURRENT AND FORMER WELLS ON THE ISLAND OF TINIAN

This page is intentionally left blank.

Table A-1. Known Current and Former Wells on the Island of Tinian

Well Name	*Other Well Names*	*Owner*	*Installed By*	*Date Well Drilled*	*Type*	*Wellhead or Measuring Point Elevation (ft)*	*Well Depth Below msl (Negative Values = Above msl)*	*Chloride Content (Various Sources)*		*Water Production (gpm) (Doan et al. 1960)*	*Water Production (gpm) (Various Sources)* [b]	*Original Function*	*Current Status*
						ft	*ft*	*Before Pumping (mg/L)*	*After Pumping (mg/L)*	*gpm*	*gpm*		
Ag-20	W-40B, Small Marpo (Japanese) Well	CNMI government	Japanese military	1930s	Dug, cement-lined trench	7.1	1.0					Watering cattle/ irrigation	Inactive
Ag-30	W-40A, Large Marpo (Japanese) Well	CNMI government	Japanese military	1930s	Dug, cement-lined trench	5.08	5.0	130	130	0	500	Watering cattle/ irrigation	Active agricultural well
Hag-N	W-43, North Hagoi		Japanese military	1930s	Dug, cement-lined trench	4.4	2.0	622				Watering cattle/ irrigation	Inactive
Hag-S	W-44, South Hagoi		Japanese military	1930s	Dug, cement-lined trench	7.54	1.0	148	360			Watering cattle/ irrigation	Inactive
M-02 [c]	W-2, Civilian Affairs Well	CNMI government	U.S. military	8/5/1997	Drilled, 6 in (15 cm) solid steel cased well	264.56	12.0		20	100		Water supply	Inactive
M-05 [c]	W-5, Asiga Well	CNMI government	U.S. military	7/31/1997	Drilled, 6 in (15 cm) solid steel cased well	108.8	13.0		75	75		Water supply	Inactive
M-07 [c]	W-7, W 100 St. Well	CNMI government	U.S. military	5/19/1995	Drilled, 6 in (15 cm) solid steel cased well	241.35	19.0			100	23	Water supply	Inactive
M-08 [c]	W-8, 110 St. Well	CNMI government	U.S. military	8/14/1997	Drilled, 6 in (15 cm) solid steel cased well	266.07	16.0	100	600	100		Water supply	Inactive
M-09 [c]	W-9, NAB #1	CNMI government	U.S. military	4/24/1995	Drilled, 6 in (15 cm) solid steel cased well	265.08	15.0		107		128	Water supply	Inactive
M-10 [c]	W-10	CNMI government	U.S. military	3/20/1997	Drilled, 6 in (15 cm) solid steel cased well	95	14.0		220	60		Water supply	Inactive
M-11 [c]	W-11, NAB #2	CNMI government	U.S. military	3/14/1995	Drilled, 6 in (15 cm) solid steel cased well	292.03	14.0				124	Water supply	Inactive
M-15 [c]	W-15, Broadway Well	CNMI government	U.S. military	5/29/1997	Drilled, 6 in (15 cm) solid steel cased well	193.84	17.0	35	70	70		Water supply	Inactive
M-16 [c]	W-16, 2nd Ave. Well	CNMI government	U.S. military	2/24/1995	Drilled, 8 in (20 cm) solid steel cased well	153.39	14.0	106	45		96	Water supply	Inactive
M-19 [c]	W-19, 8th Ave. Well	CNMI government	U.S. military	6/5/1997	Drilled, 6 in (15 cm) solid steel cased well	247.92	14.0				30	Water supply	Inactive
M-21 [c]	WOP-151/152, W-21, Mendiola Well, 67th St. Well	CNMI government	U.S. military	1/11/1997	Drilled, 6 in (15 cm) solid steel cased well	243.29	17.0	80		60	49	Water supply	Active agricultural well
M-22 [c]	W-22, 90th St. Well	CNMI government	U.S. military	6/30/1997	Drilled, 6 in (15 cm) solid steel cased well	222.73	8.0		150	40		Water supply	Inactive
M-25 [d]	W-25, East Side Well	Unknown	U.S. military	09/19/87?	Drilled, 6 in (15 cm) solid steel cased well	211.94	88.0	196		30		Water supply	Inactive
M-26 [d]	UPW-008, W-26, 59th St. Well	Unknown	U.S. military	1987?	Drilled, 6 in (15 cm) solid steel cased well	340.83	30.0	40		35		Water supply	Active agricultural well
M-29 [c]	W-29, West Field Well	CNMI government	U.S. military	2/12/1997	Drilled, 6 in (15 cm) solid steel cased well	247.04	168.0					Water supply	Inactive
M-33 [c]	W-33, 72nd St. Well	CNMI government	U.S. military	8/20/1997	Drilled, 6 in (15 cm) solid steel cased well	235.63	10.0	50				Water supply	Inactive
M-35 [c]	W-35	CNMI government	U.S. military	7/25/1997	Drilled, 6 in (15 cm) solid steel cased well	257.23	13.0					Water supply	Inactive
M-39 [c]	W-39	CNMI government	U.S. military	5/15/1997	Drilled, 6 in (15 cm) solid steel cased well	238.93	11.0		150			Water supply	Inactive

Well Name	Other Well Names	Owner	Installed By	Date Well Drilled	Type	Wellhead or Measuring Point Elevation (ft)	Well Depth Below msl (Negative Values = Above msl)	Chloride Content (Various Sources)		Water Production (gpm) (Doan et al. 1960)	Water Production (gpm) (Various Sources) [b]	Original Function	Current Status
						ft	ft	Before Pumping (mg/L)	After Pumping (mg/L)	gpm	gpm		
Maui Well No. 1	W-41, formerly Municipal Well, Marpo Well	CNMI government	U.S. military	1945	Dug, out-of-service municipal water supply well (Maui-type horizontal construction - constructed of 240 steel cylindrical bomb crates joined end to end and perforated)	9.76	-9.8	97	100		780	Drinking water supply well	Out of service
Maui Well No. 2	Municipal Well	CNMI government	CNMI government	2000	Municipal water supply well (Maui-type horizontal construction)						875	Drinking water supply well	Active use
ObsB		Unknown	USGS	2/2/1991	USGS 4 in (10 cm) monitoring piezometer (PVC pipe-cased)	7.45	0.5					Groundwater monitoring well	Unknown
Pala	W-45	Tinian Palacios family	Japanese military	1930s	3 ft (0.9 m) diameter, hand dug well	65	3.0	185	200				Active use
Taga		CNMI government	Ancient Chamorro	Unknown	Shallow-dug well								Unknown
TH-01		CNMI government	USGS	9/17/1996	USGS 12 in (30 cm) monitoring well	117.46	13				165	Groundwater monitoring well	Unknown
TH-02		CNMI government	USGS	4/28/1997	USGS 8 in (20 cm) monitoring well	158.86	94					Groundwater monitoring well	Unknown
TH-03		CNMI government	USGS	10/24/1996	USGS 8 in (20 cm) monitoring well	109.05	22				105	Groundwater monitoring well	Unknown
TH-04		CNMI government	USGS	12/13/1993	USGS 8 in (20 cm) monitoring well	72.18	18				108	Groundwater monitoring well	Unknown
TH-05		CNMI government	USGS	6/21/1995	USGS 8 in (20 cm) monitoring well	120.85	18				92	Groundwater monitoring well	Unknown
TH-06		CNMI government	USGS	3/2/1995	USGS 6 in (15 cm) monitoring well	309.07	13				57	Groundwater monitoring well	Unknown
TH-07		CNMI government	USGS	1/20/1995	USGS 6 in (15 cm) monitoring well	343.84	20				50	Groundwater monitoring well	Unknown
TH-08		CNMI government	USGS	1/29/1993	USGS 4 in (10 cm) monitoring well	8.24	92					Groundwater monitoring well	Unknown
TH-09		CNMI government	USGS	2/3/1993	USGS 4 in (10 cm) monitoring well	6.7	92					Groundwater monitoring well	Unknown
TH-10		CNMI government	USGS	10/9/1996	USGS 8 in (20 cm) monitoring well	163.74	16				68	Groundwater monitoring well	Unknown
TH-11		CNMI government	USGS	2/25/1997	USGS 6 in (15 cm) monitoring well	339.66	19				63	Groundwater monitoring well	Unknown
TH-12		CNMI government	USGS	1/8/1997	USGS 8 in (20 cm) monitoring well	146.41	13				72	Groundwater monitoring well	Unknown
TH1-9		CNMI government	USGS	7/26/1995	USGS 8 in (20 cm) monitoring well	550	29					Groundwater monitoring well	Unknown
TH-1X		CNMI government	USGS	10/1/1996	USGS 6 in (15 cm) monitoring well	116.99	15					Groundwater monitoring well	Unknown
TH-22		CNMI government	USGS	10/16/1996	USGS 8 in (20 cm) monitoring well	96.61	16				110	Groundwater monitoring well	Unknown

Well Name	*Other Well Names*	*Owner*	*Installed By*	*Date Well Drilled*	*Type*	*Wellhead or Measuring Point Elevation (ft)*	*Well Depth Below msl (Negative Values = Above msl)*	*Chloride Content (Various Sources)*		*Water Production (gpm) (Doan et al. 1960)*	*Water Production (gpm) (Various Sources)* [b]	*Original Function*	*Current Status*
						ft	*ft*	*Before Pumping (mg/L)*	*After Pumping (mg/L)*	*gpm*	*gpm*		
TH-24		CNMI government	USGS	4/10/1997	USGS 8 in (20 cm) monitoring well		9				3	Groundwater monitoring well	Unknown
TH-4X		CNMI government	USGS	5/5/1994	USGS 8 in (20 cm) monitoring well	71.89	268					Groundwater monitoring well	Unknown
Ushi		U.S. military	U.S. military	9/6/1987	Military water supply well	98.47	19.0					Non-potable water supply well	Unknown
W-1	Masalog	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	255.29	7.2	40	85	55		Water supply	Inactive
W-12	E 100 St. Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	184.43	14.6	100	High	60		Water supply	Inactive
W-13	Park Row Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	59.96	15.0					Water supply	Inactive
W-14	42nd St. Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	242.63	12.4	30	40	35		Water supply	Inactive
W-17	86th St. Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	244	4.0					Water supply	Inactive
W-18A	98th St. Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	289.3	100.7	38		8		Water supply	Inactive
W-18B	98th St. B Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	285	75.0	35		8		Water supply	Inactive
W-20	New 110th St. Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	258	10.0		600	10		Water supply	Inactive
W-23	Mil. Gov. #2	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	294.4	-126.4					Water supply	Inactive
W-24	Central Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	247.27	15.7	70				Water supply	Inactive
W-27	Mil. Gov. Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	284.5	30.5			0		Water supply	Inactive
W-28	West Side Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	253.75	12.3					Water supply	Inactive
W-3	Lasso	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	202.18	31.3					Water supply	Inactive
W-30	84th St. Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	255.5	-18.5					Water supply	Inactive
W-31	Hilo Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	257.58	11.4			0		Water supply	Inactive
W-32	113th St. Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	223	14.0					Water supply	Inactive
W-34 [a]	Island Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	298.24	17.8					Water supply	Inactive
W-36		U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	125	12.0					Water supply	Inactive
W-37		U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	100	14.0					Water supply	Inactive
W-38		U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	277.83	22.2			0		Water supply	Inactive
W-4	Gurgaon	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	225.31	6.7		35	60		Water supply	Inactive
W-46 [a]		U.S. military	U.S. military	WWII Period	Hand-dug well	50	-45.0	650				Water supply	Inactive

Well Name	***Other Well Names***	***Owner***	***Installed By***	***Date Well Drilled***	***Type***	***Wellhead or Measuring Point Elevation (ft)***	***Well Depth Below msl (Negative Values = Above msl)***	***Chloride Content (Various Sources)***		***Water Production (gpm) (Doan et al. 1960)***	***Water Production (gpm) (Various Sources)*** [b]	***Original Function***	***Current Status***
						ft	***ft***	***Before Pumping (mg/L)***	***After Pumping (mg/L)***	***gpm***	***gpm***		
W-47 [a]		U.S. military	U.S. military	WWII Period	Hand-dug well	35	-20.0					Water supply	Inactive
W-6	96th St. Well	U.S. military	U.S. military	WWII Period	Drilled, 6 in (15 cm) solid steel cased well	239.41	15.1	16	100	100		Water supply	Inactive
WOP-197-01		CNMI government	Unknown	10/7/2011	4 in (10 cm) Schedule 80 PVC pipe							Groundwater monitoring well (for landfill siting study)	Unknown
WOP-197-02		CNMI government	Unknown	9/24/2011	4 in (10 cm) Schedule 80 PVC pipe						193	Groundwater monitoring well (for landfill siting study)	Unknown
WOP-197-03		CNMI government	Unknown	10/3/2011	Schedule 80 PVC pipe well							Groundwater monitoring well (for landfill siting study)	Unknown

Notes: [a] Present location of this well is unknown.
[b] Rates based on pump test data (mostly USGS 2002). Values do not necessarily represent maximum sustainable rates.
[c] Rehabilitated by USGS.
[d] Rehabilitated by private party.
Blanks = unknown

Legend: cm = centimeter; CNMI = Commonwealth of the Northern Mariana Islands; ft = foot/feet; gpm = gallon per minute; in = inch; lpm = liter per minute; m = meter; msl = mean sea level; NA = not applicable; mg/L = part per million; PVC = polyvinyl chloride; USGS = U.S. Geological Survey; WWII = World War II

Sources USGS 2000, 2002; Doan et al. 1960