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).

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.

Figure 9. Groundwater Model Domain

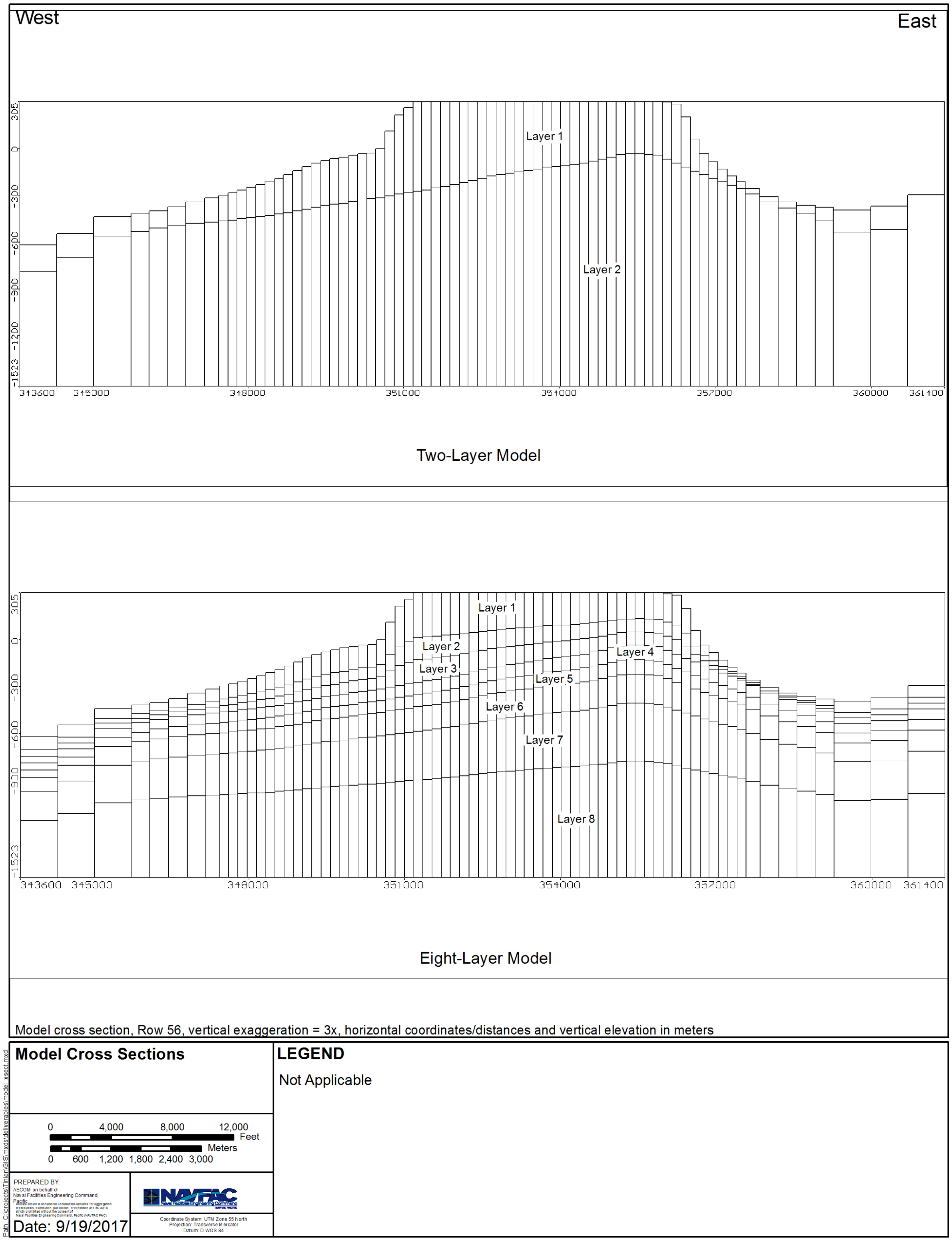

Figure 10. Model Cross Sections

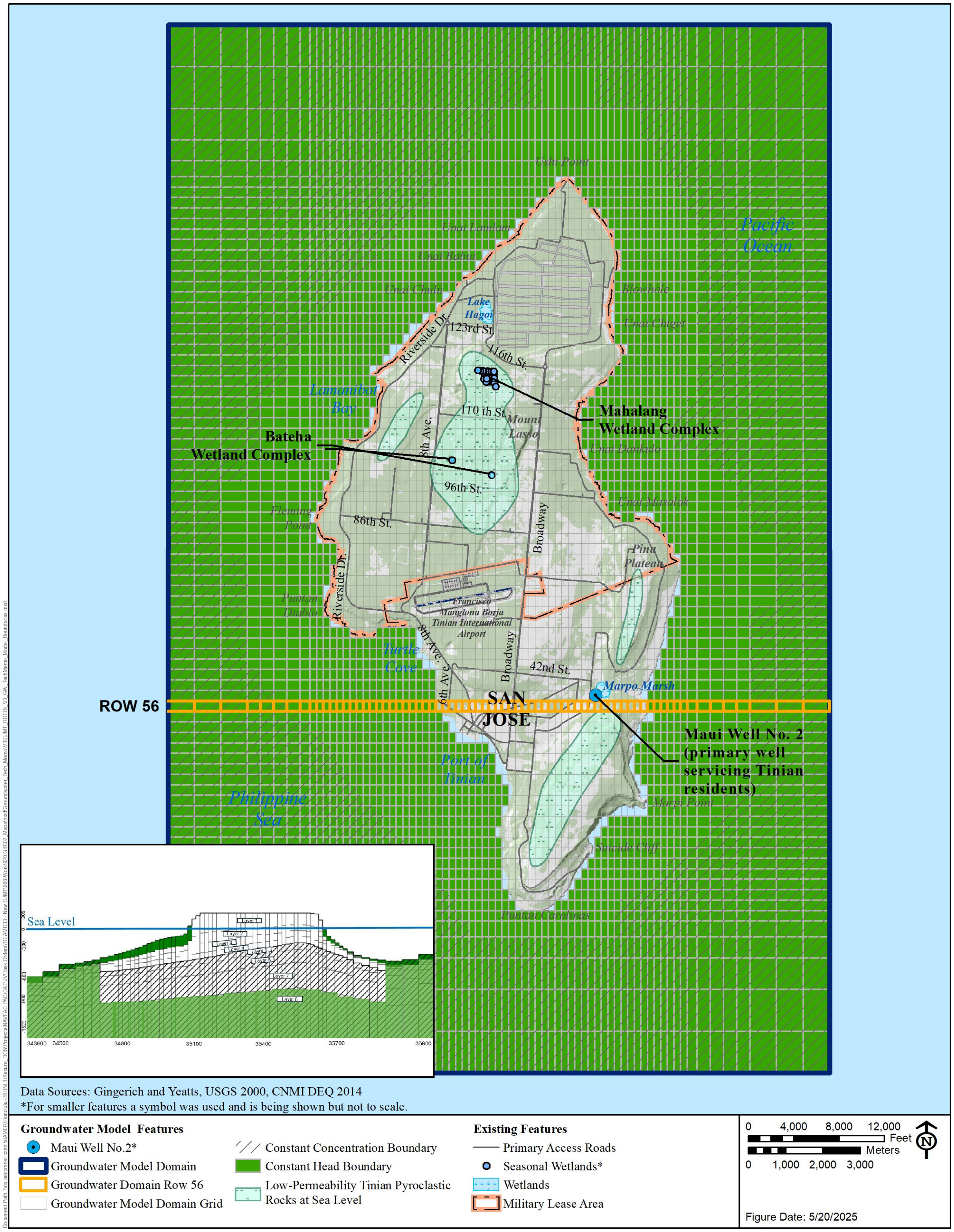

Figure 11. Model Boundaries

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.

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.

Figure 12. Model Head Residuals

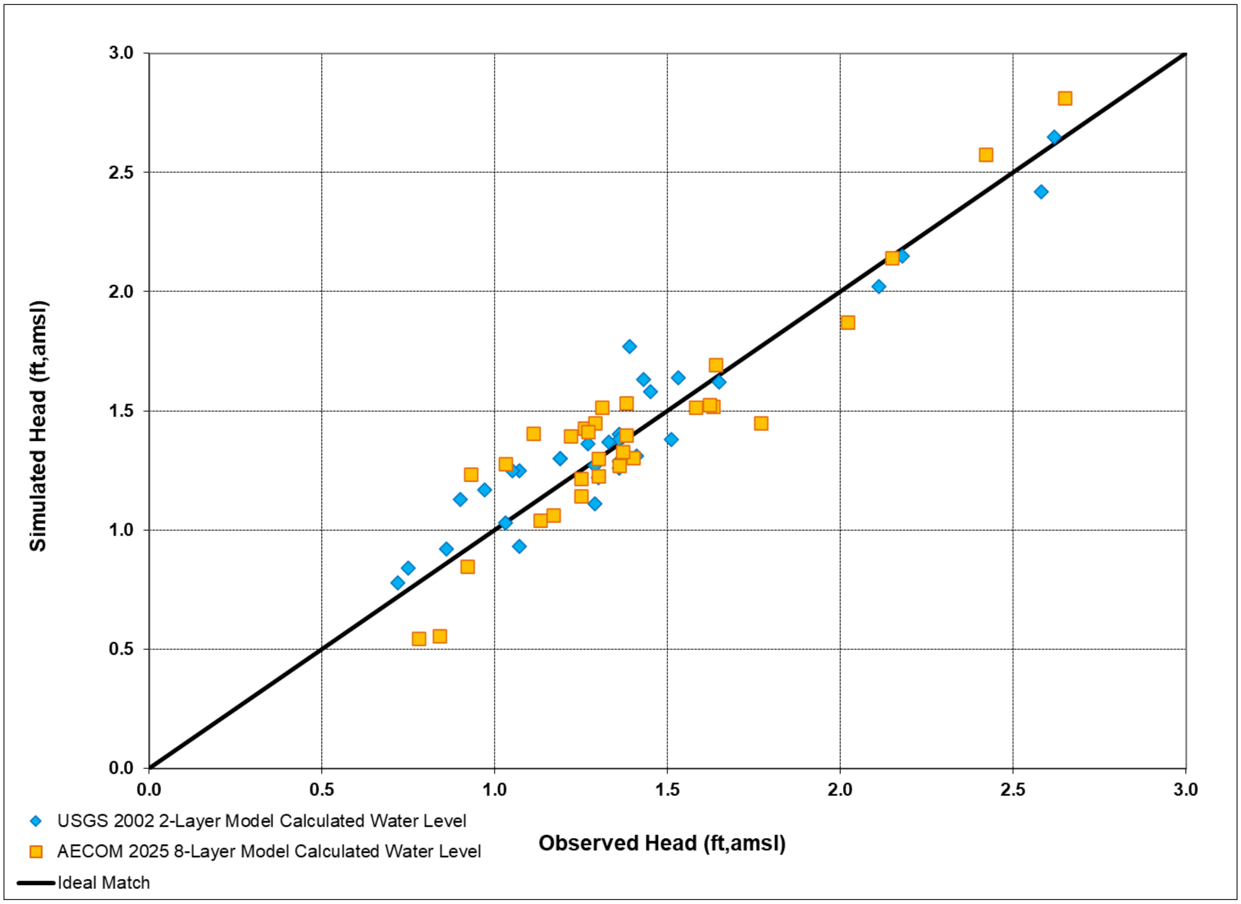

Figure 13. Scatter Plot of Observed Heads vs. Simulated Heads

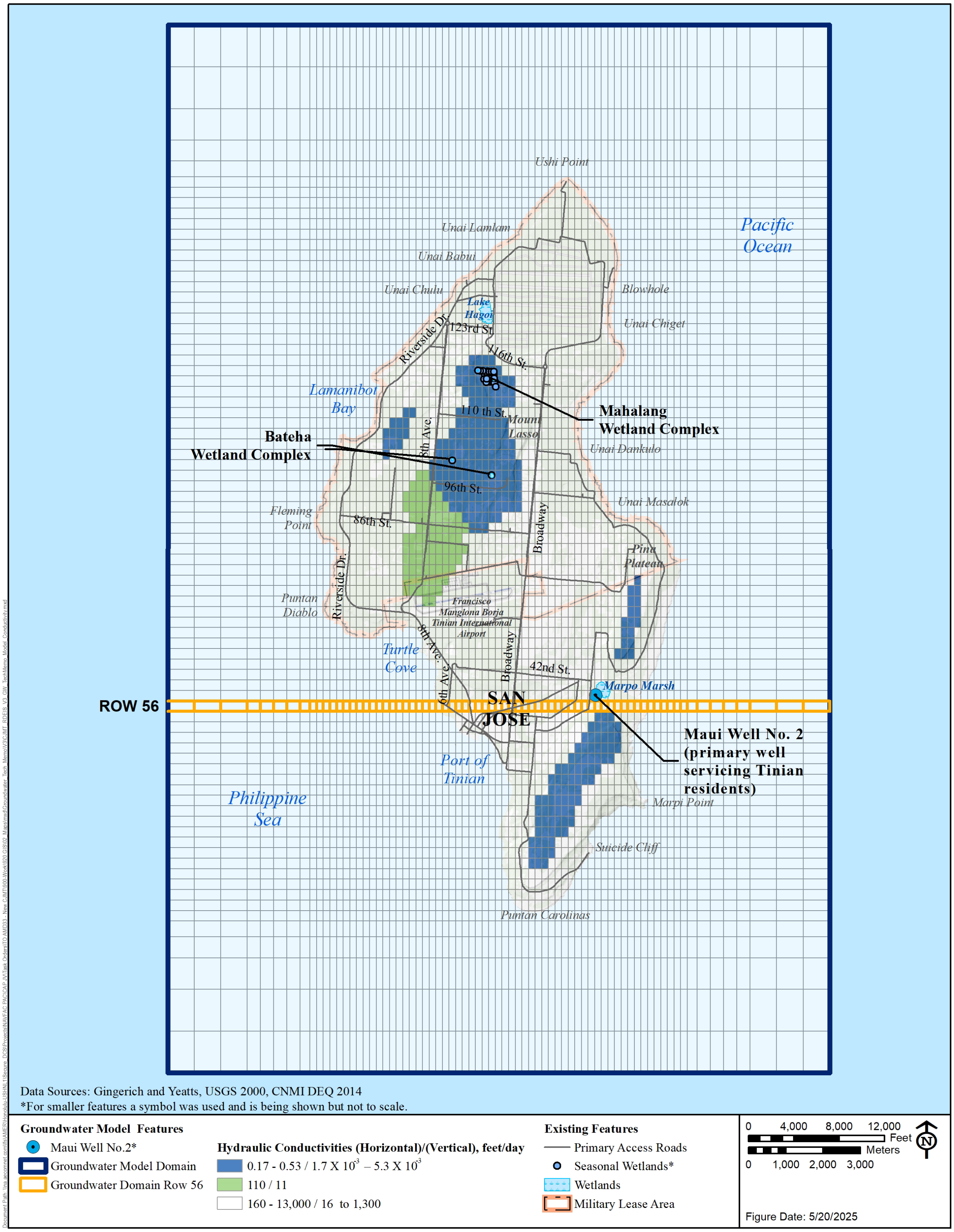

Figure 14. Model Hydraulic Conductivity Values and Distribution in Model Layer 1

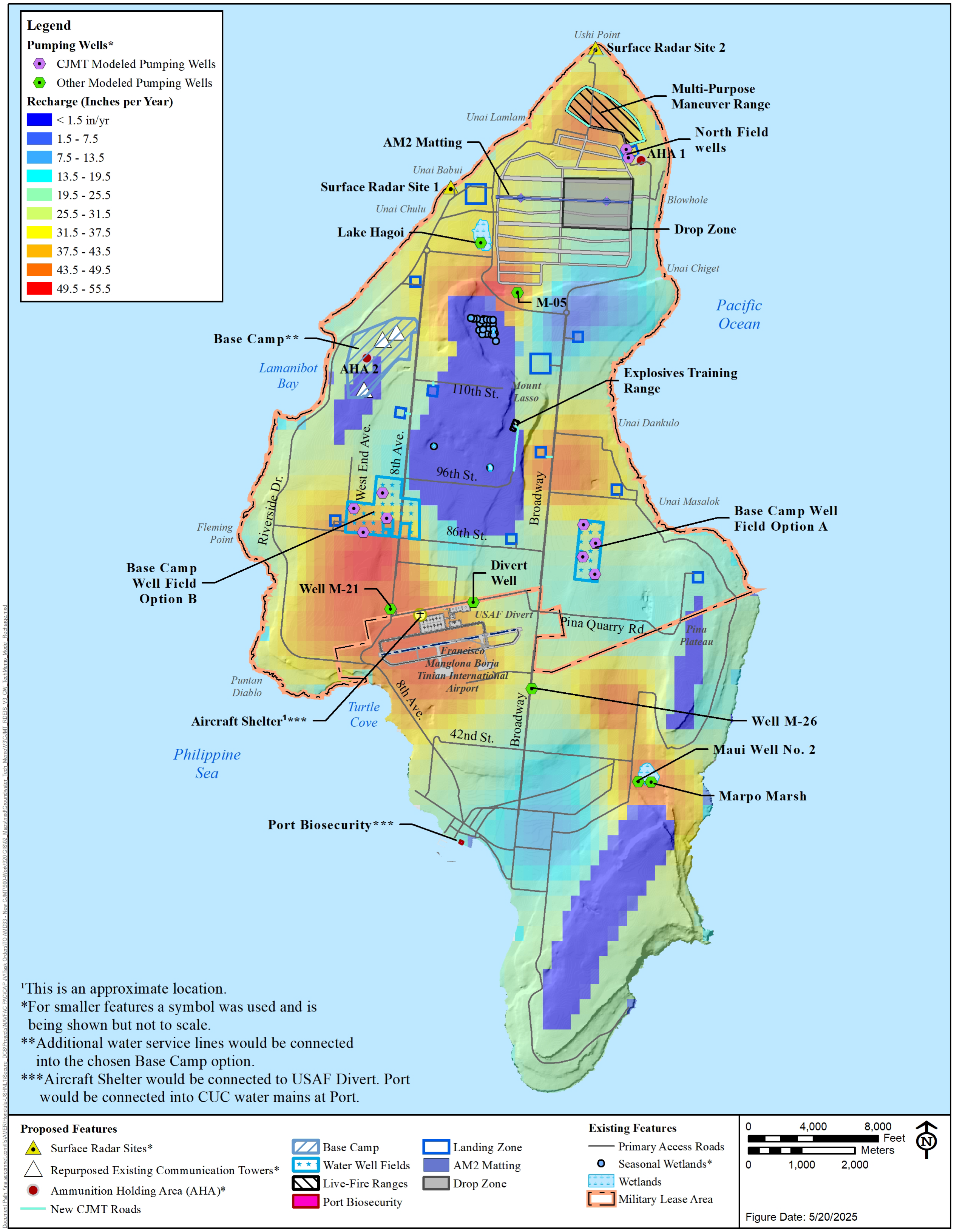

Figure 15. Model Recharge

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 run time to approximate "steady state" was 250 years.

The drought scenario is conservatively assumed to be two consecutive years of reduced rainfall, represented in the model by an infiltration of 10 percent of the modeled normal infiltration rate (approximately 30 inches per year). When simulating the drought, the model was run for 250 years (after reaching "steady state") during which a period of 2 years reduced recharge was applied in the time of 150–152 years. 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	—			—	—

<table>
<tr><th>Well</th><th>Scenario 1 (Baseline)</th><th>Scenario 2</th><th>Scenario 3</th><th>Scenario 4</th><th>Scenario 5</th></tr>
<tr><td>Well Field B-01</td><td>—</td><td>—</td><td>—</td><td rowspan="4">21,777</td><td rowspan="4">21,777</td></tr>
<tr><td>Well Field B-02</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>Well Field B-03</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>Well Field B-04</td><td>—</td><td>—</td><td>—</td></tr>
</table>

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	168
M-21	48	48	107	48	107
M-26	32	51	100	51	100
M-05	41	42	70	42	70
Divert Well	32	32	33	32	33
North Field-01	590	590	897	590	897
North Field-02	665	664	1,120	664	1,197
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	30
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. 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. Therefore, 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 Bureau of Environmental and Coastal Quality.

5.6 GROUNDWATER FLOW DIRECTIONS

Modeled groundwater heads and groundwater flow directions under current conditions (Scenario 1) and the proposed action under drought conditions (Scenarios 3 and 5) from flow modeling are plotted in Figure 21 through Figure 23.

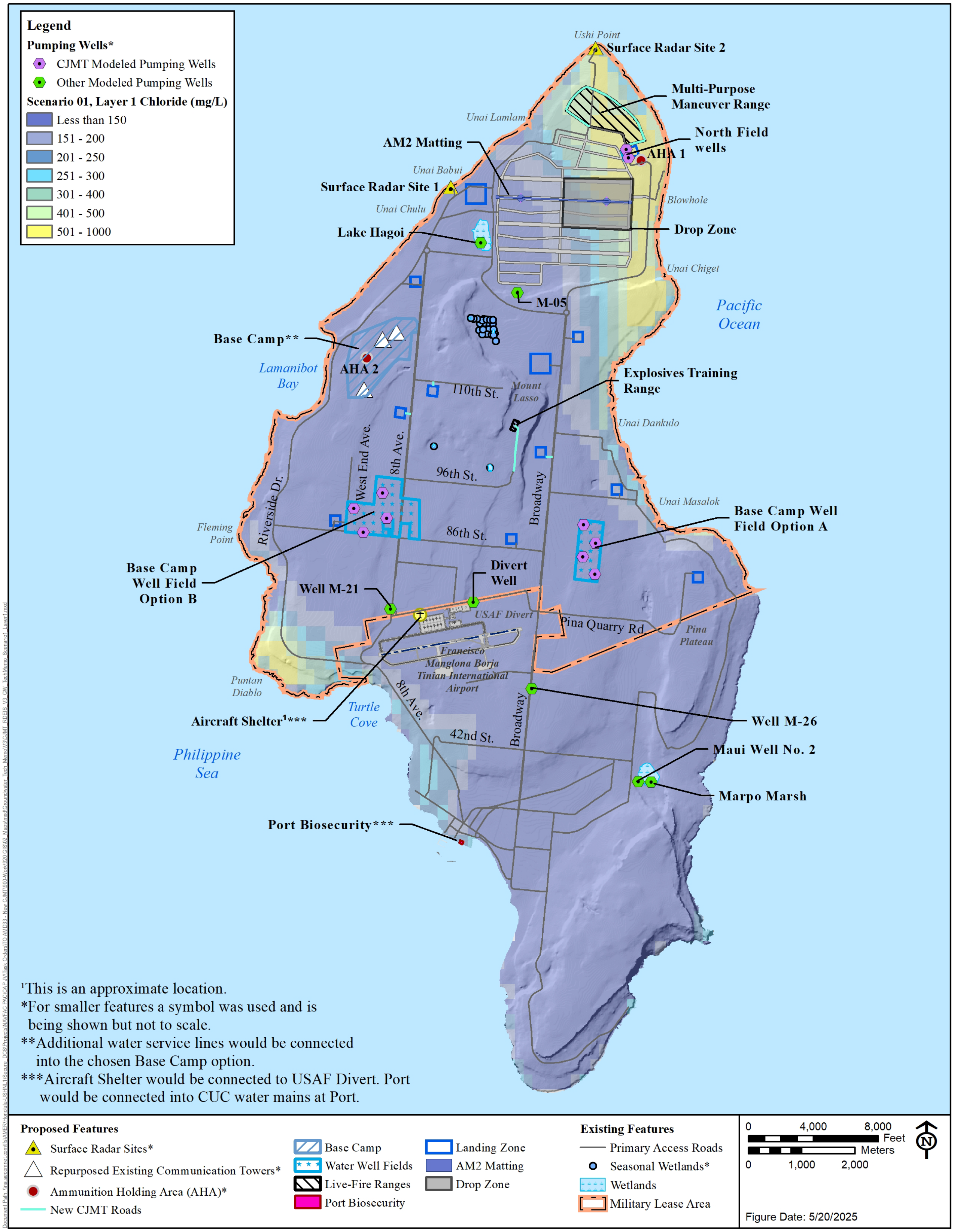

Figure 16.1. Modeled Chloride Concentrations for Layer 1 – Scenario 1

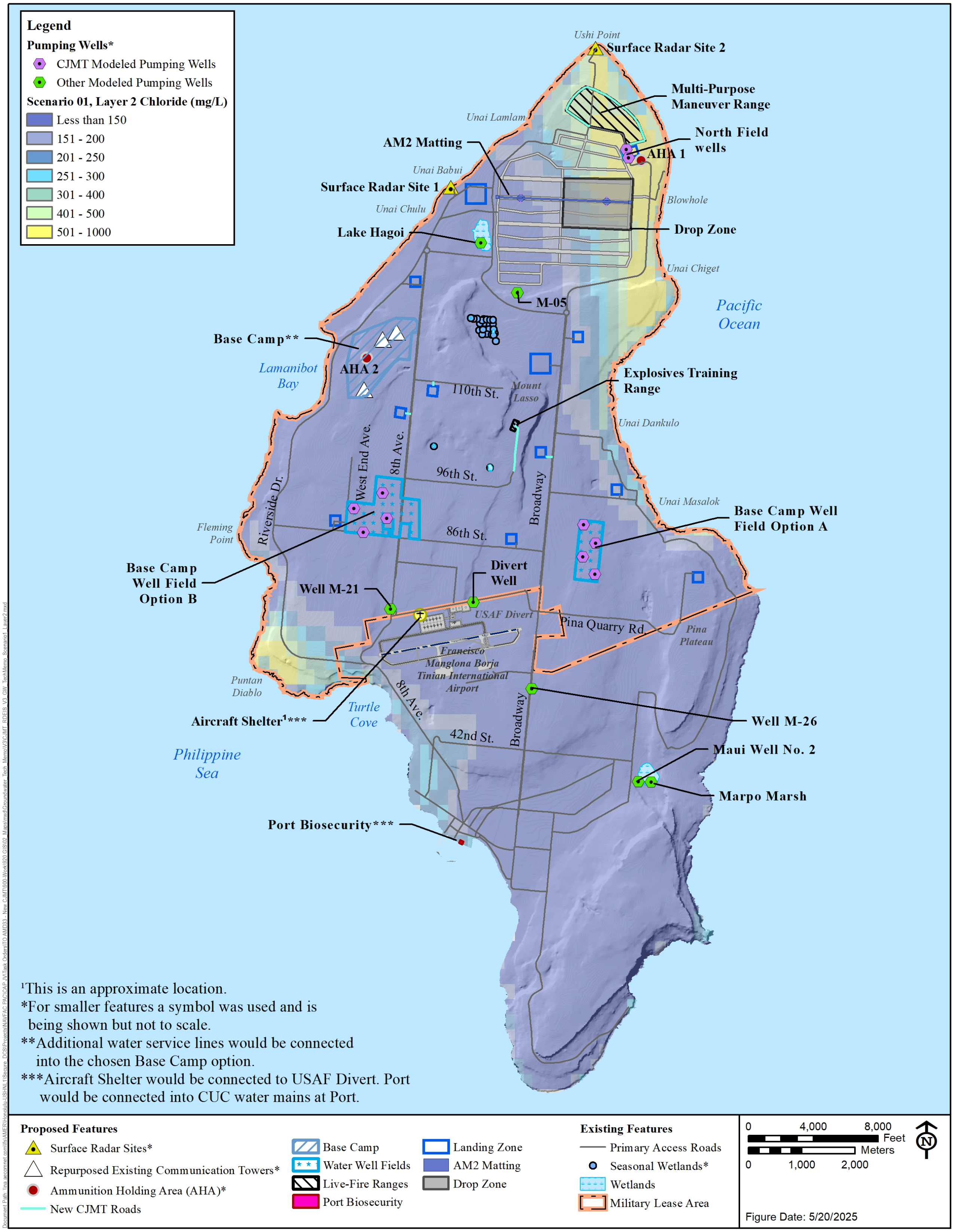

Figure 16.2. Modeled Chloride Concentrations for Layer 2 – Scenario 1

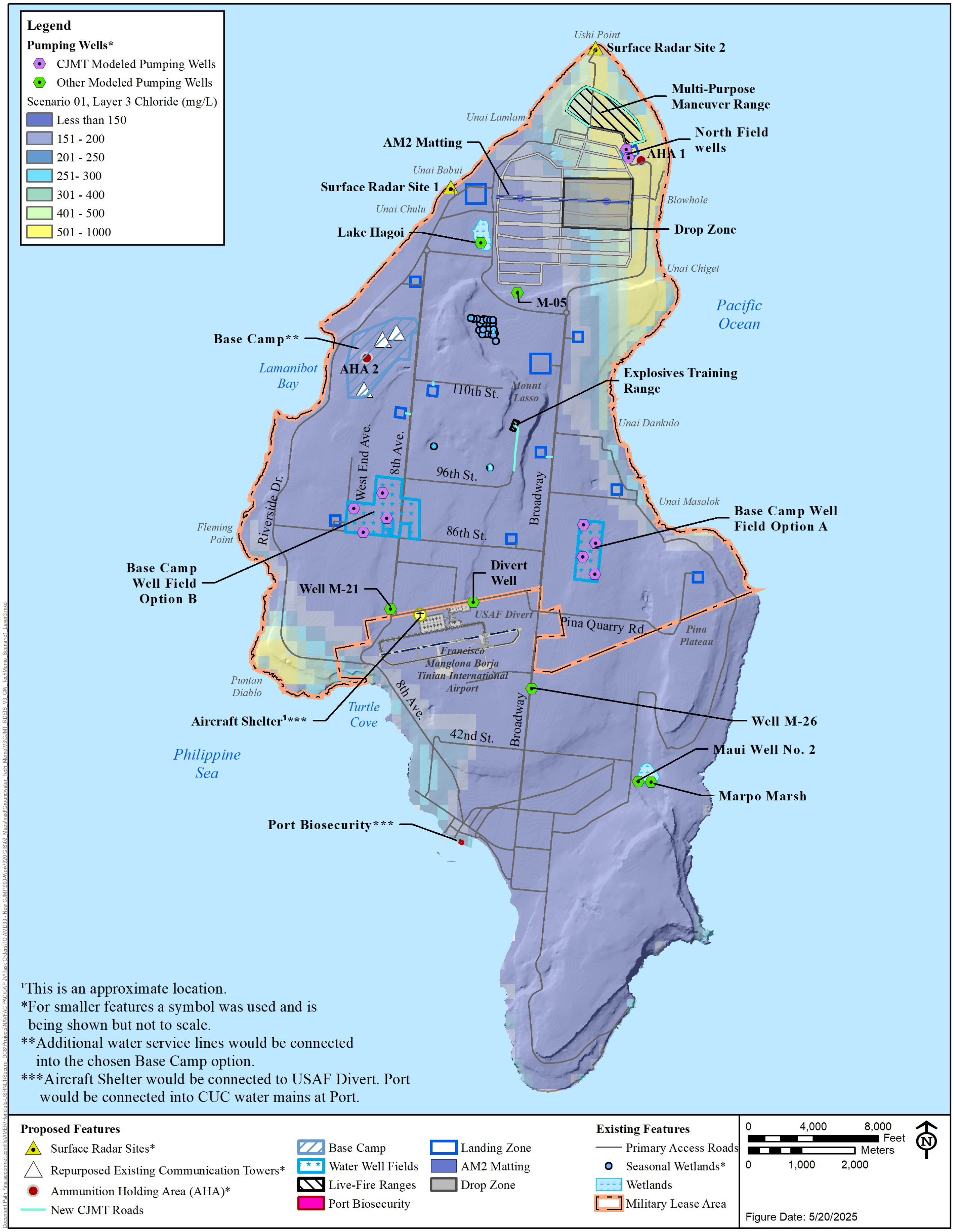

Figure 16.3. Modeled Chloride Concentrations for Layer 3 – Scenario 1

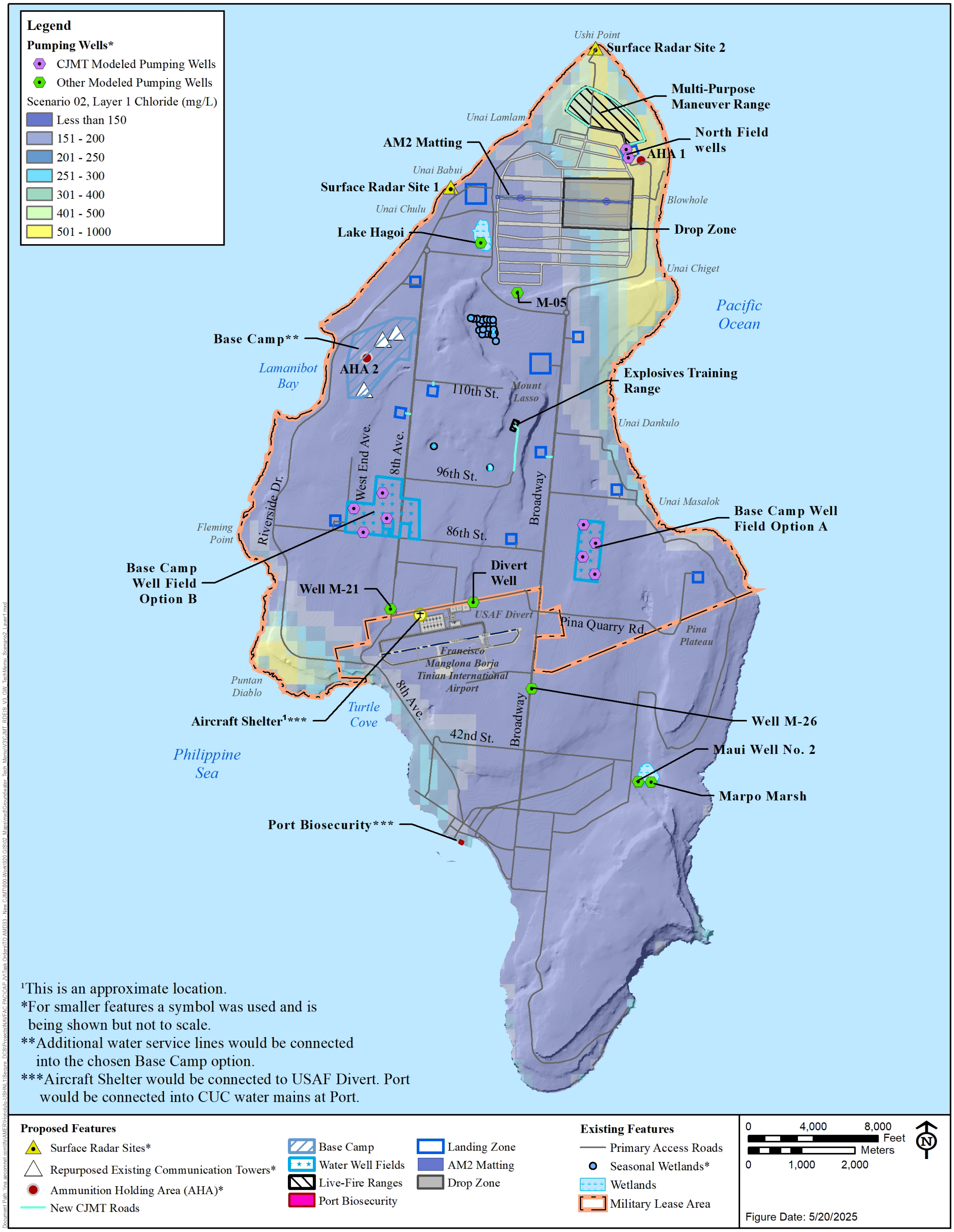

Figure 17.1. Modeled Chloride Concentrations for Layer 1 – Scenario 2

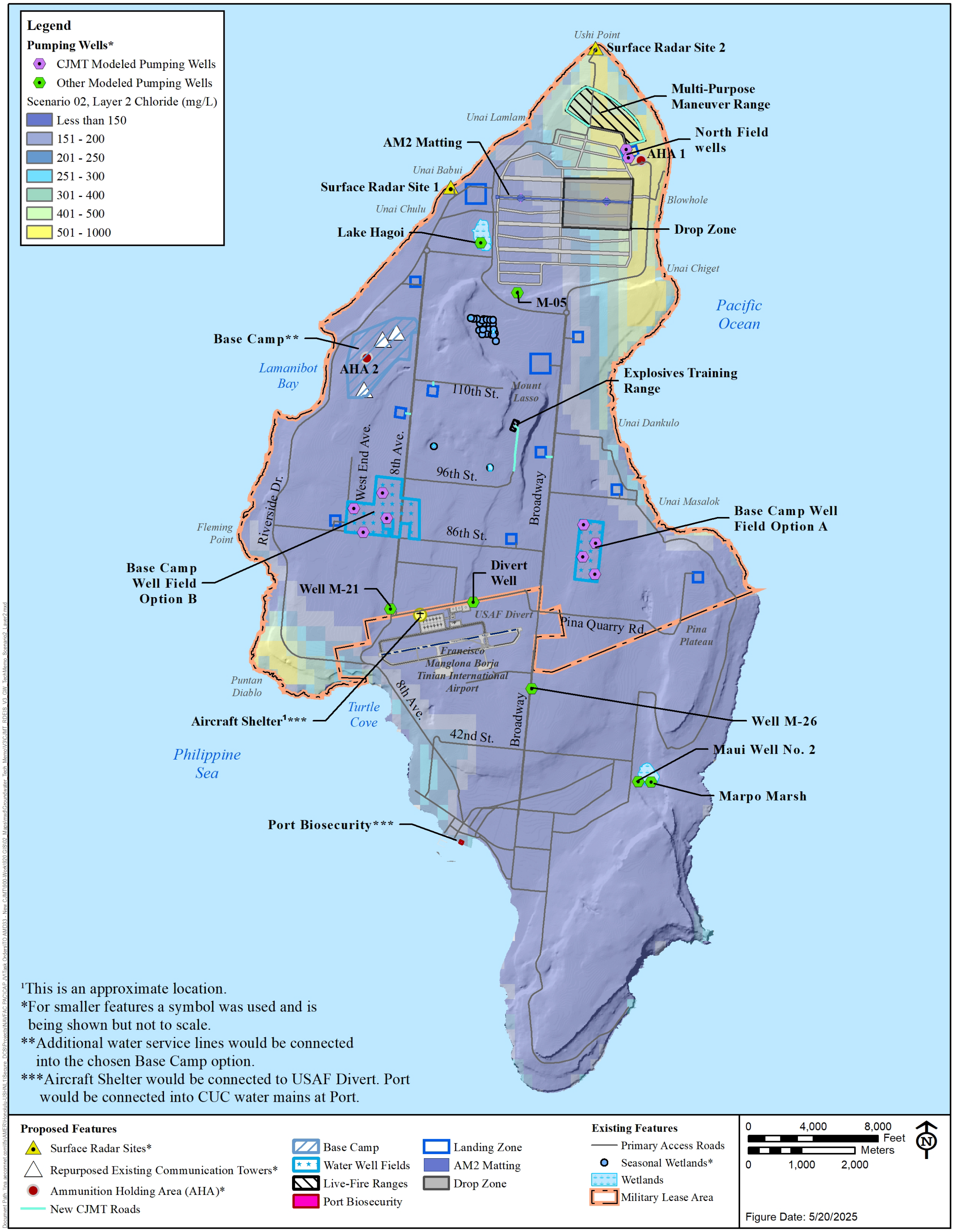

Figure 17.2. Modeled Chloride Concentrations for Layer 2 – Scenario 2

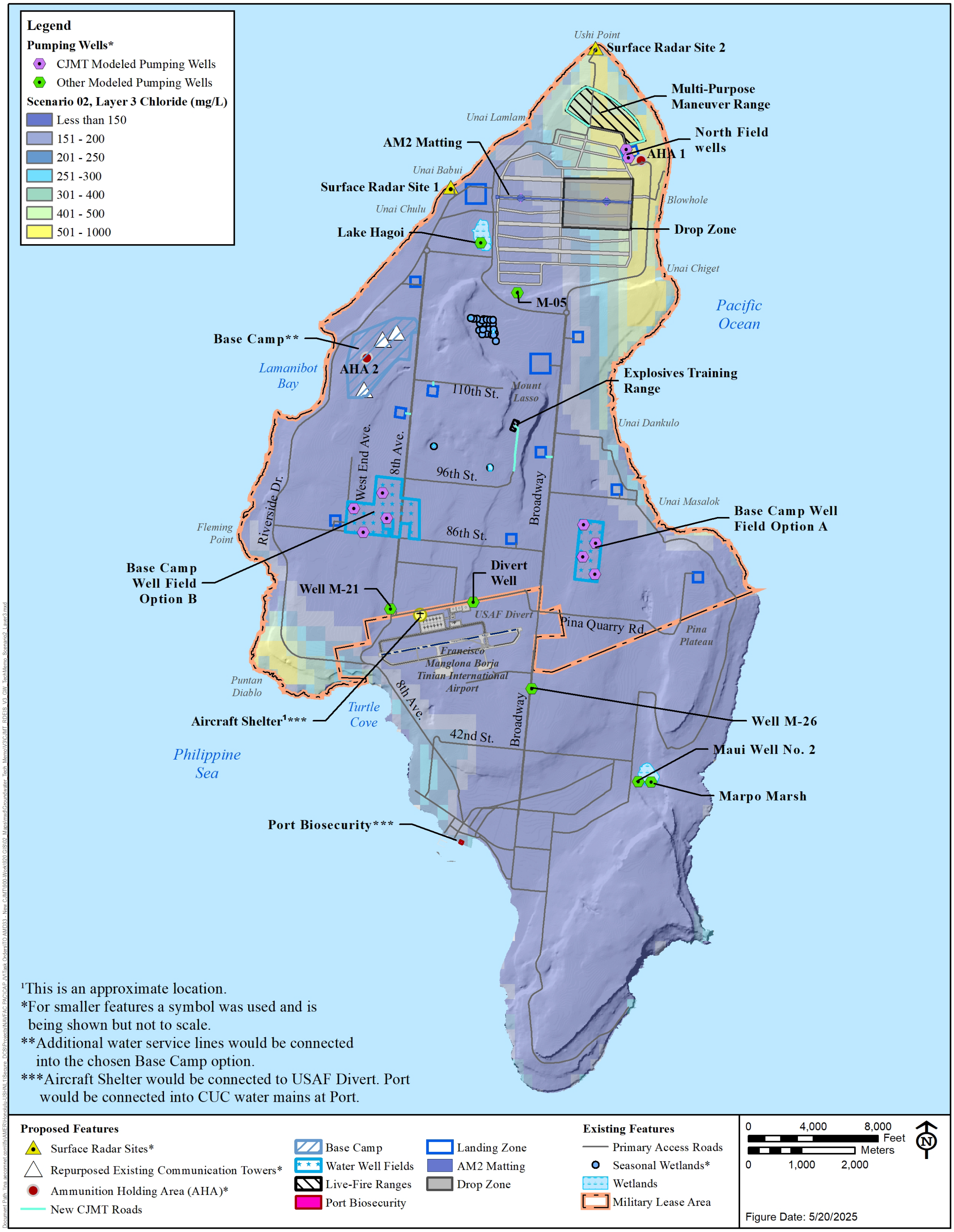

Figure 17.3. Modeled Chloride Concentrations for Layer 3 – Scenario 2

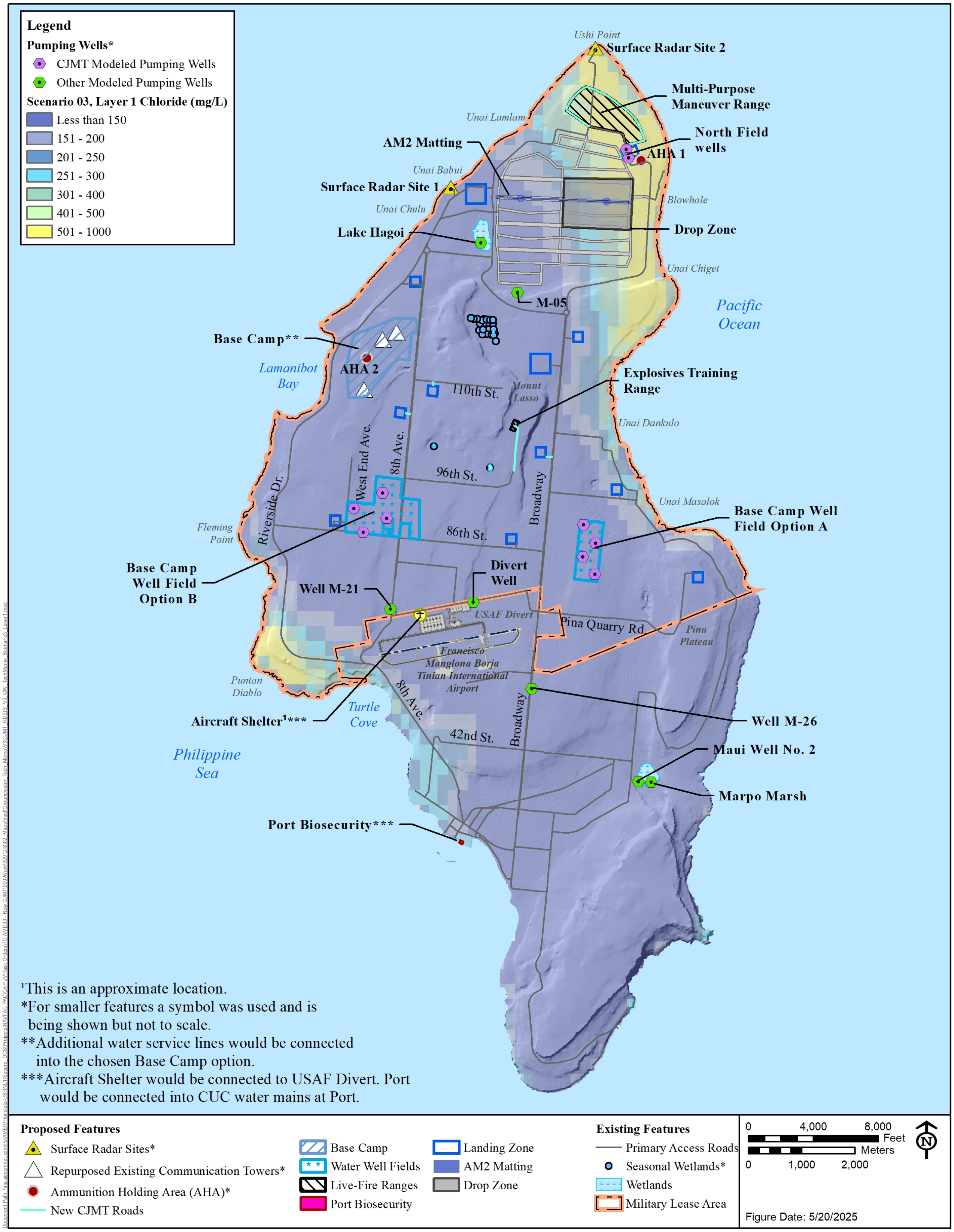

Figure 18.1. Modeled Chloride Concentrations for Layer 1 – Scenario 3

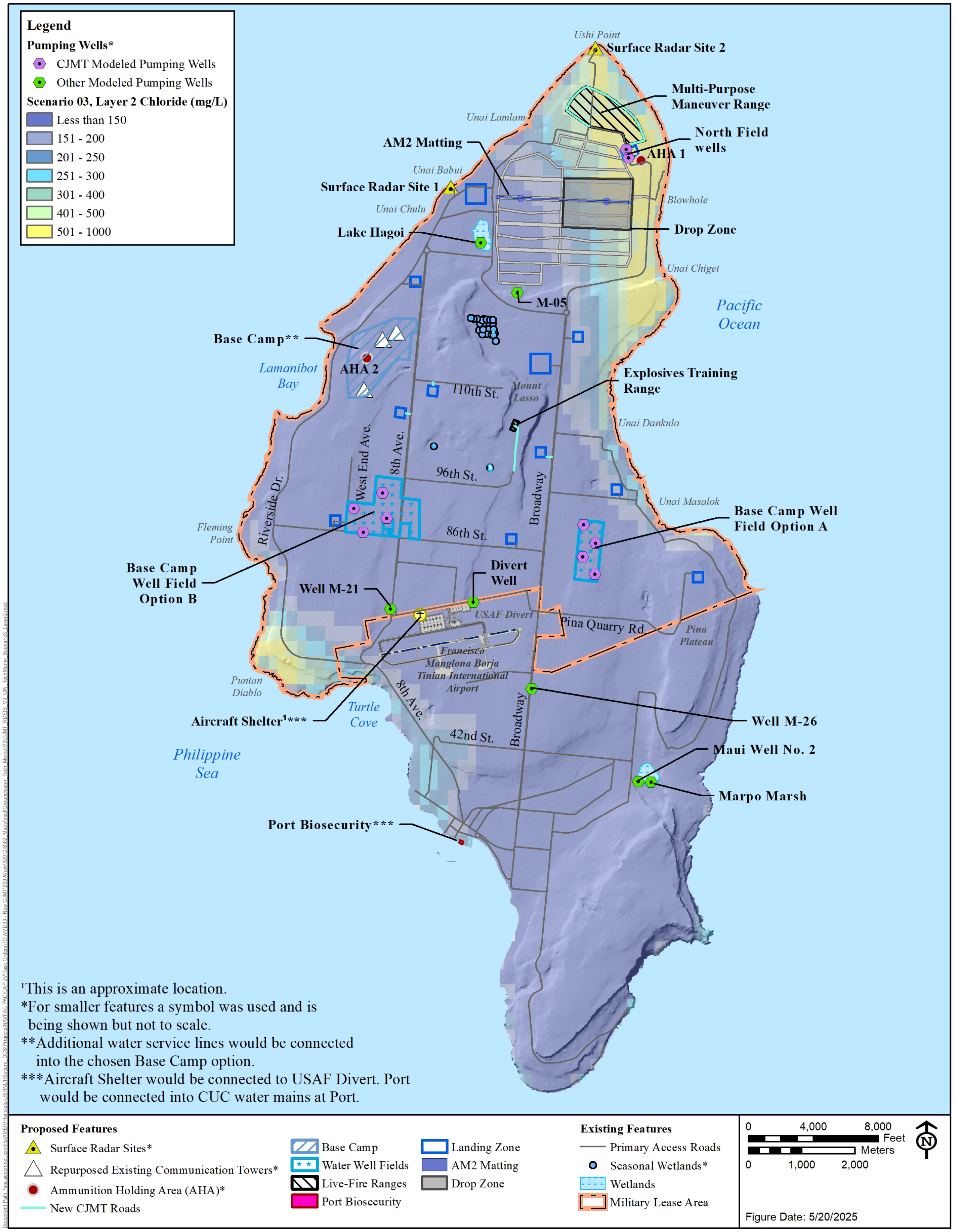

Figure 18.2. Modeled Chloride Concentrations for Layer 2 – Scenario 3

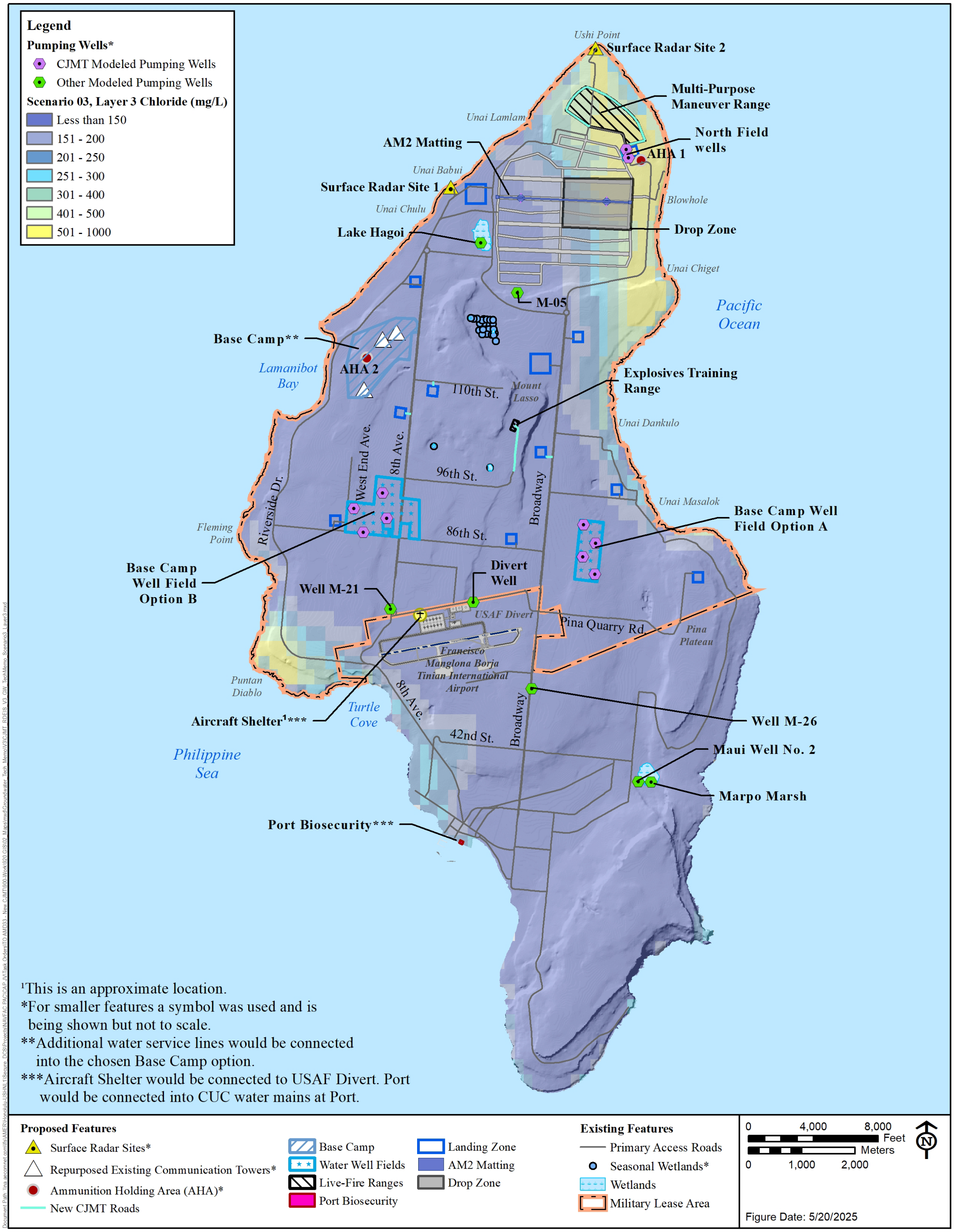

Figure 18.3. Modeled Chloride Concentrations for Layer 3 – Scenario 3

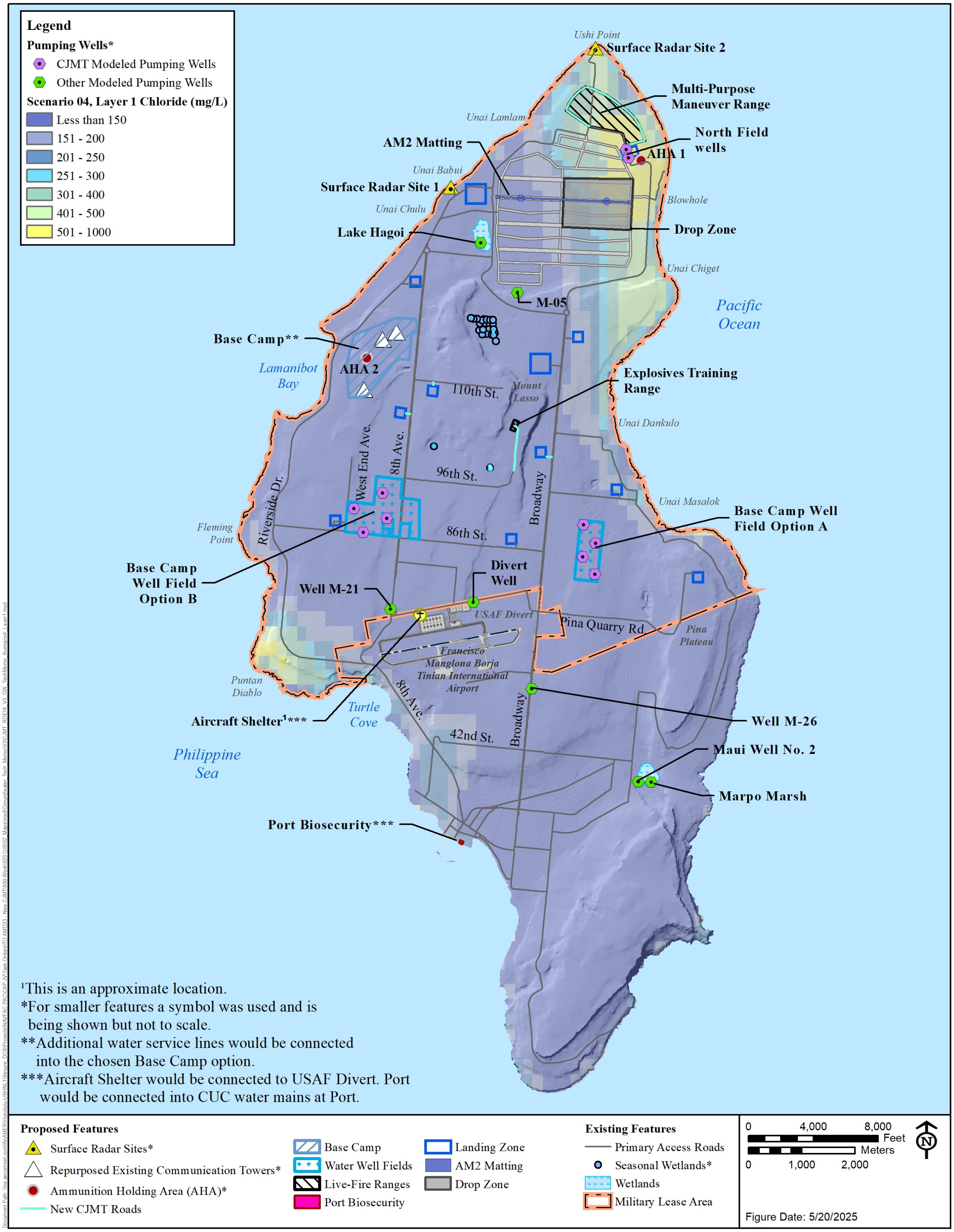

Figure 19.1. Modeled Chloride Concentrations for Layer 1 – Scenario 4

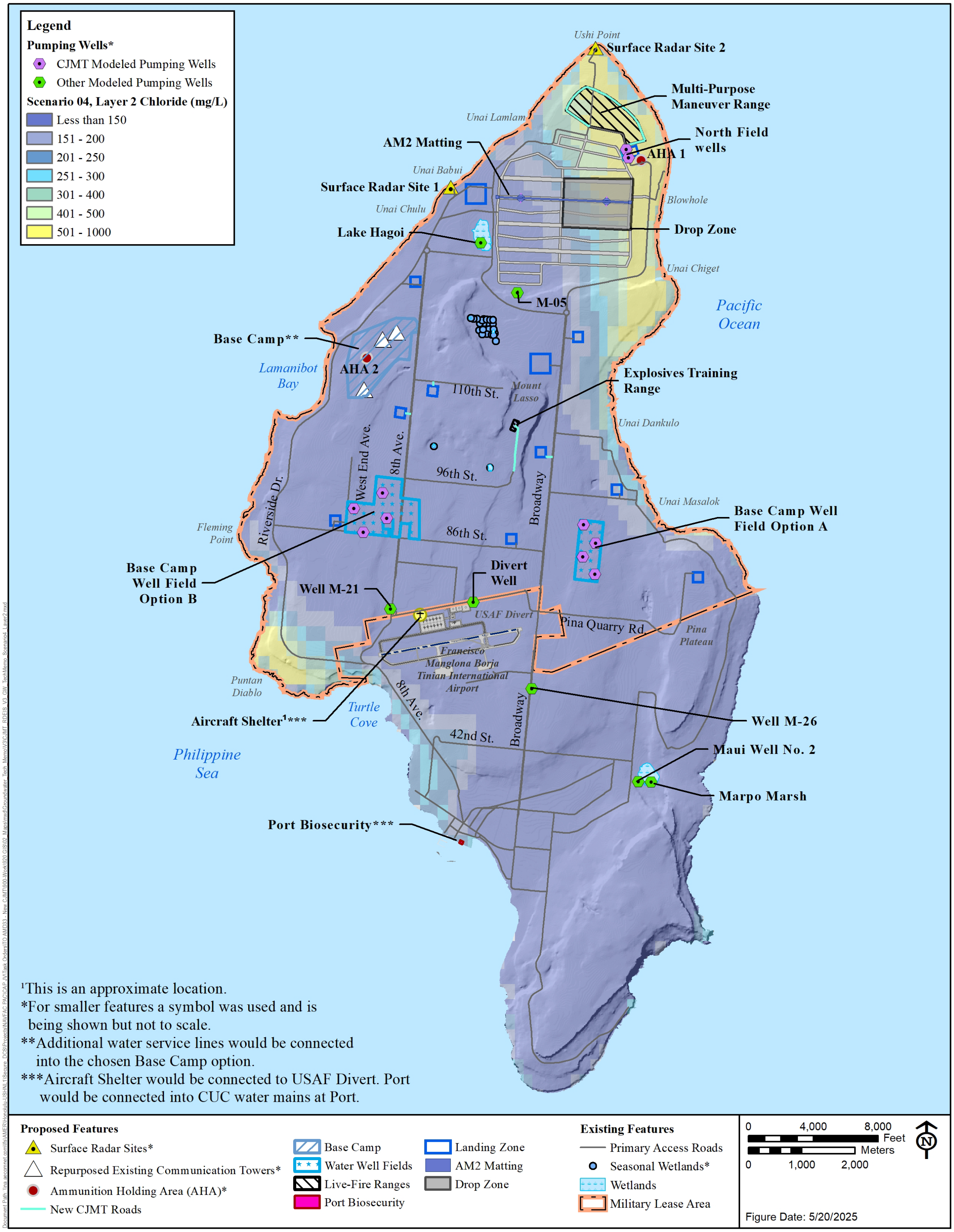

Figure 19.2. Modeled Chloride Concentrations for Layer 2 – Scenario 4

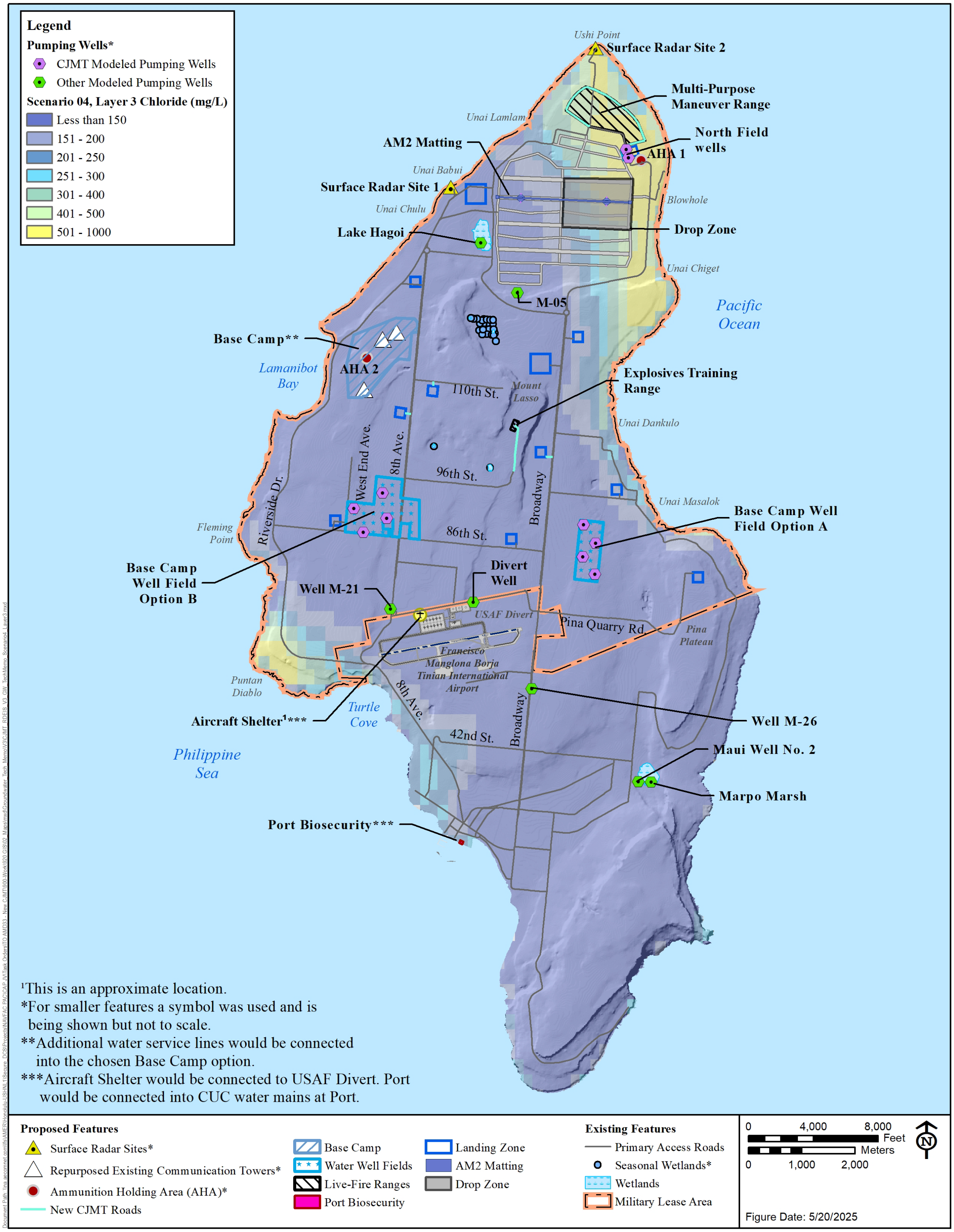

Figure 19.3. Modeled Chloride Concentrations for Layer 3 – Scenario 4

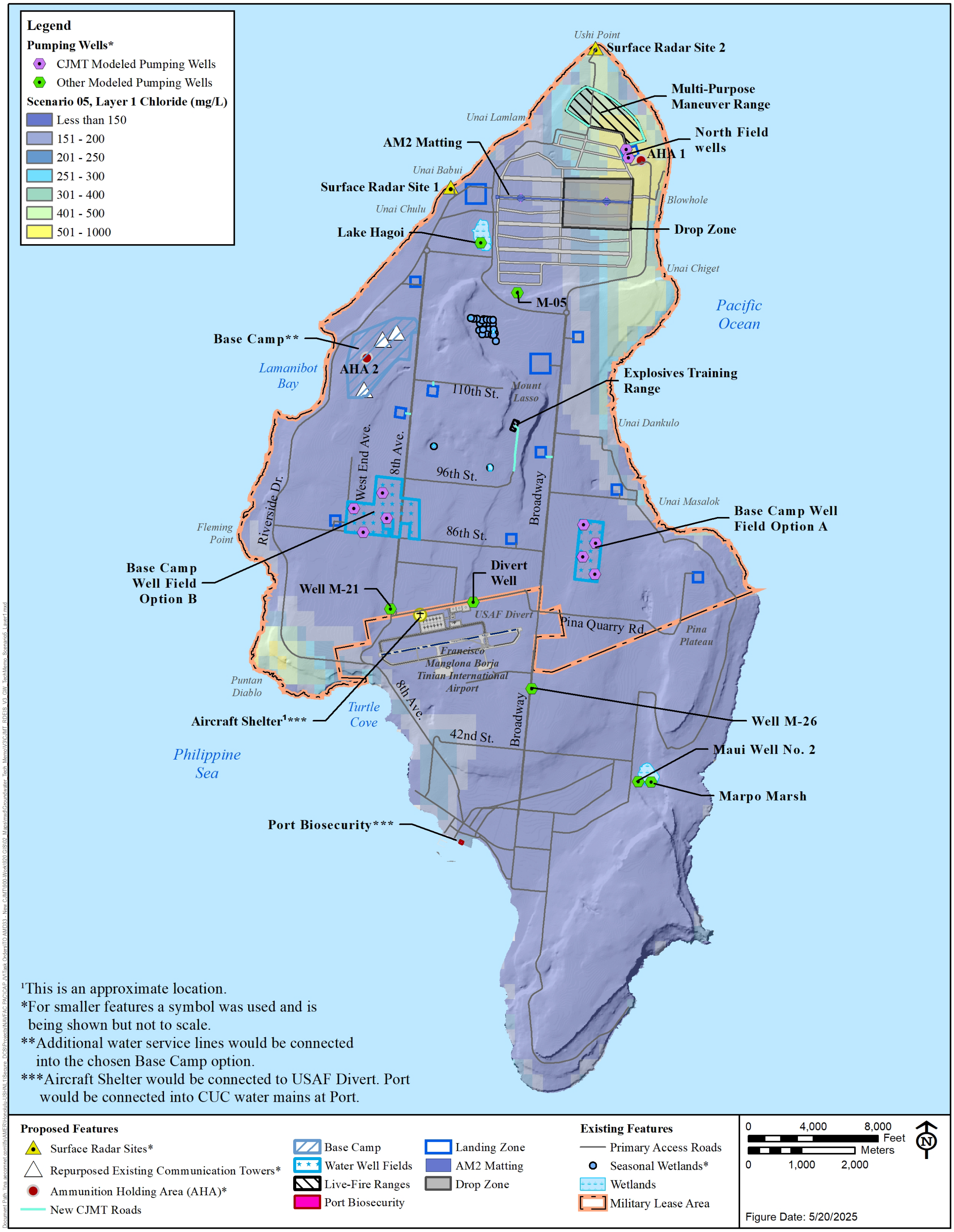

Figure 20.1. Modeled Chloride Concentrations for Layer 1 – Scenario 5

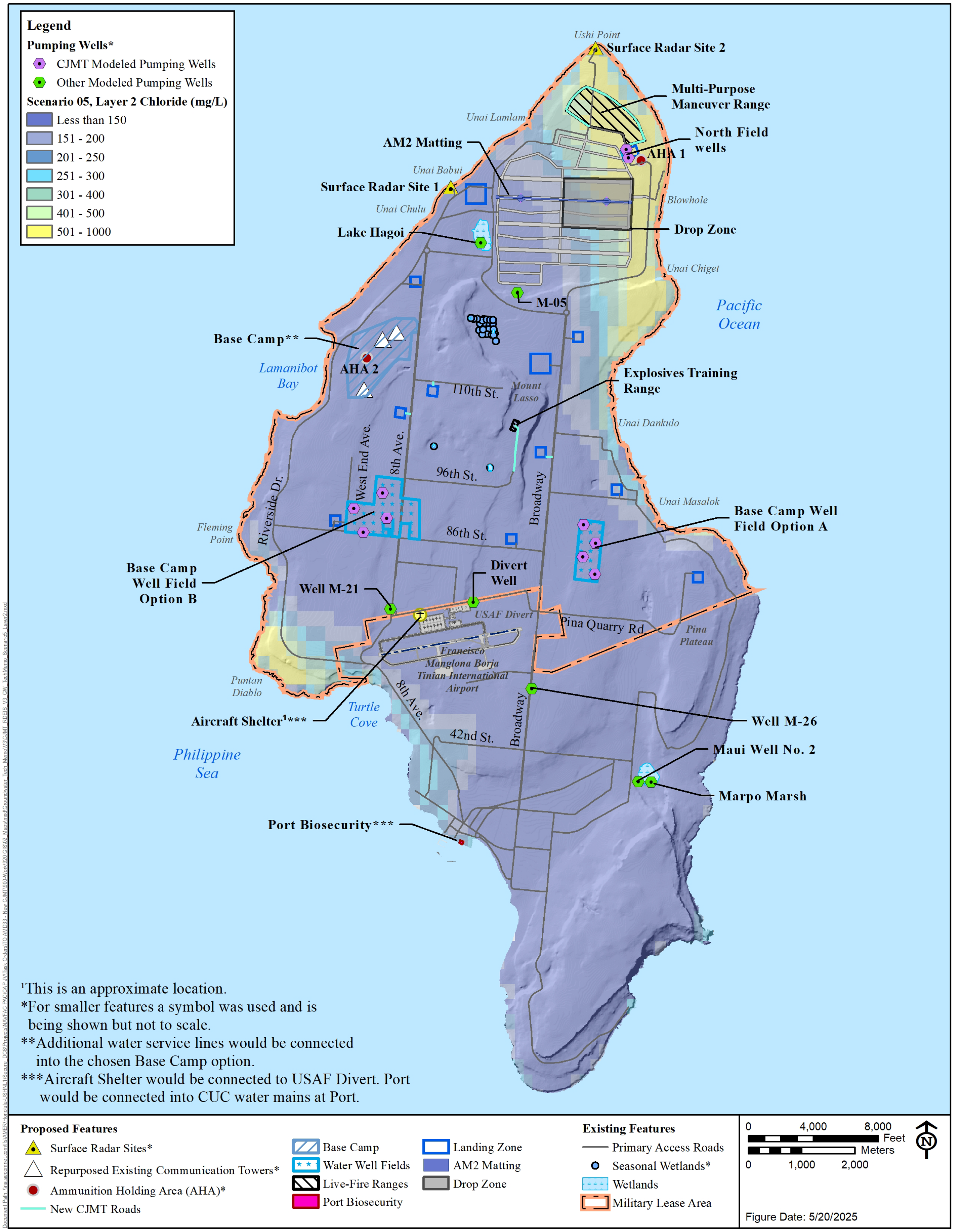

Figure 20.2. Modeled Chloride Concentrations for Layer 2 – Scenario 5

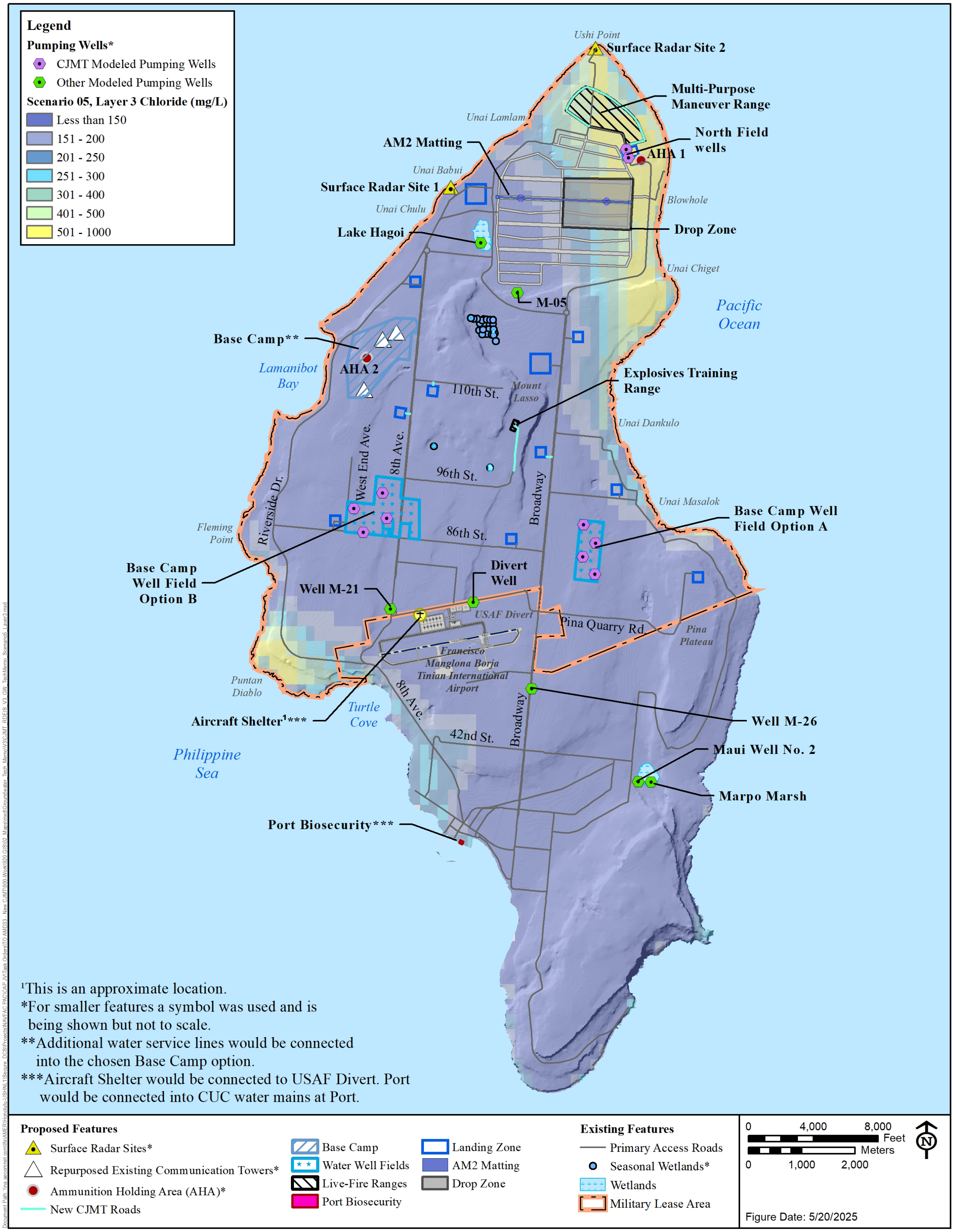

Figure 20.3. Modeled Chloride Concentrations for Layer 3 – Scenario 5

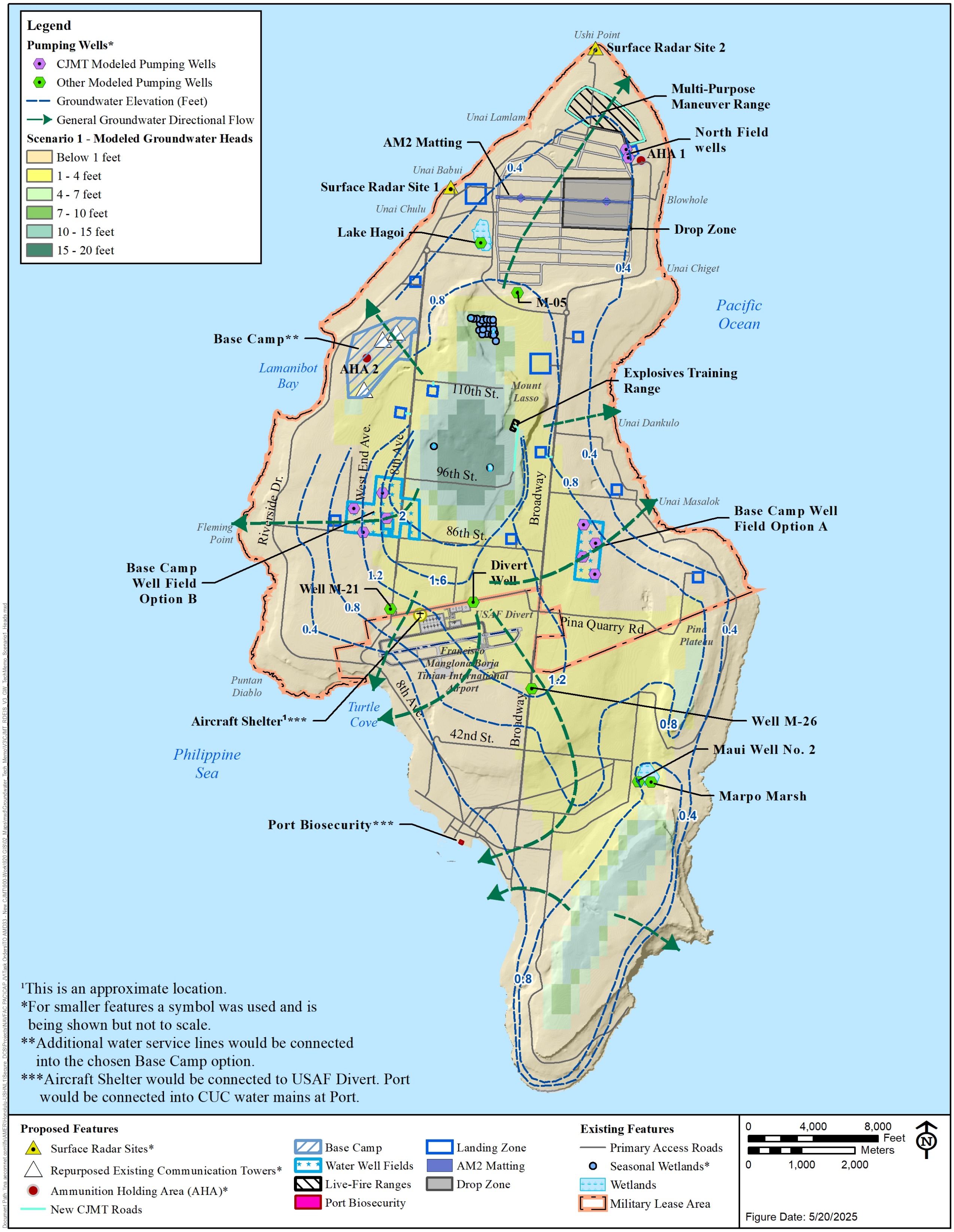

Figure 21. Modeled Groundwater Heads and Groundwater Flow Directions – Scenario 1

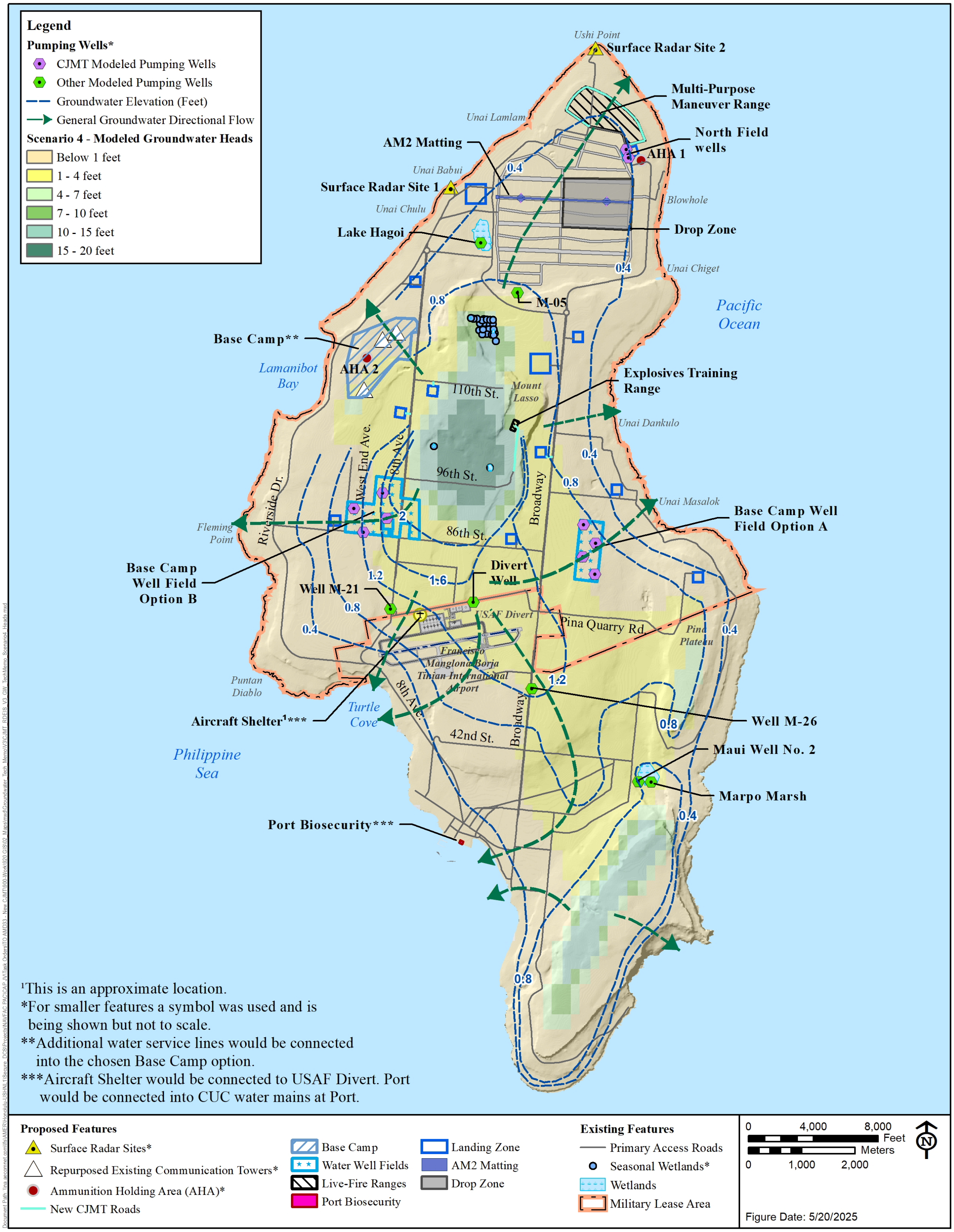

Figure 22. Modeled Groundwater Heads and Groundwater Flow Directions – Scenario 4

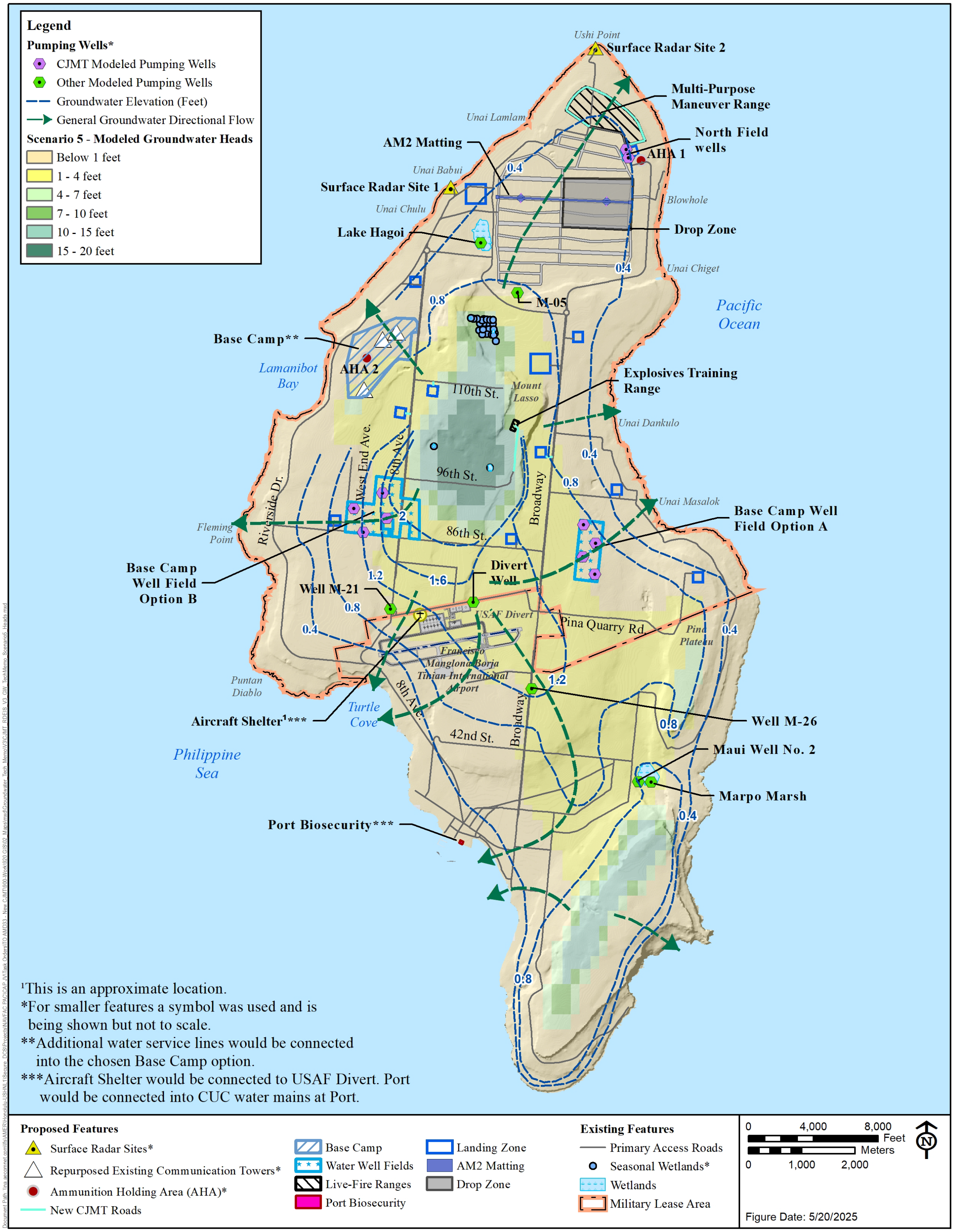

Figure 23. Modeled Groundwater Heads and Groundwater Flow Directions – Scenario 5

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 yo 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 concentration. 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 page intentionally left blank.