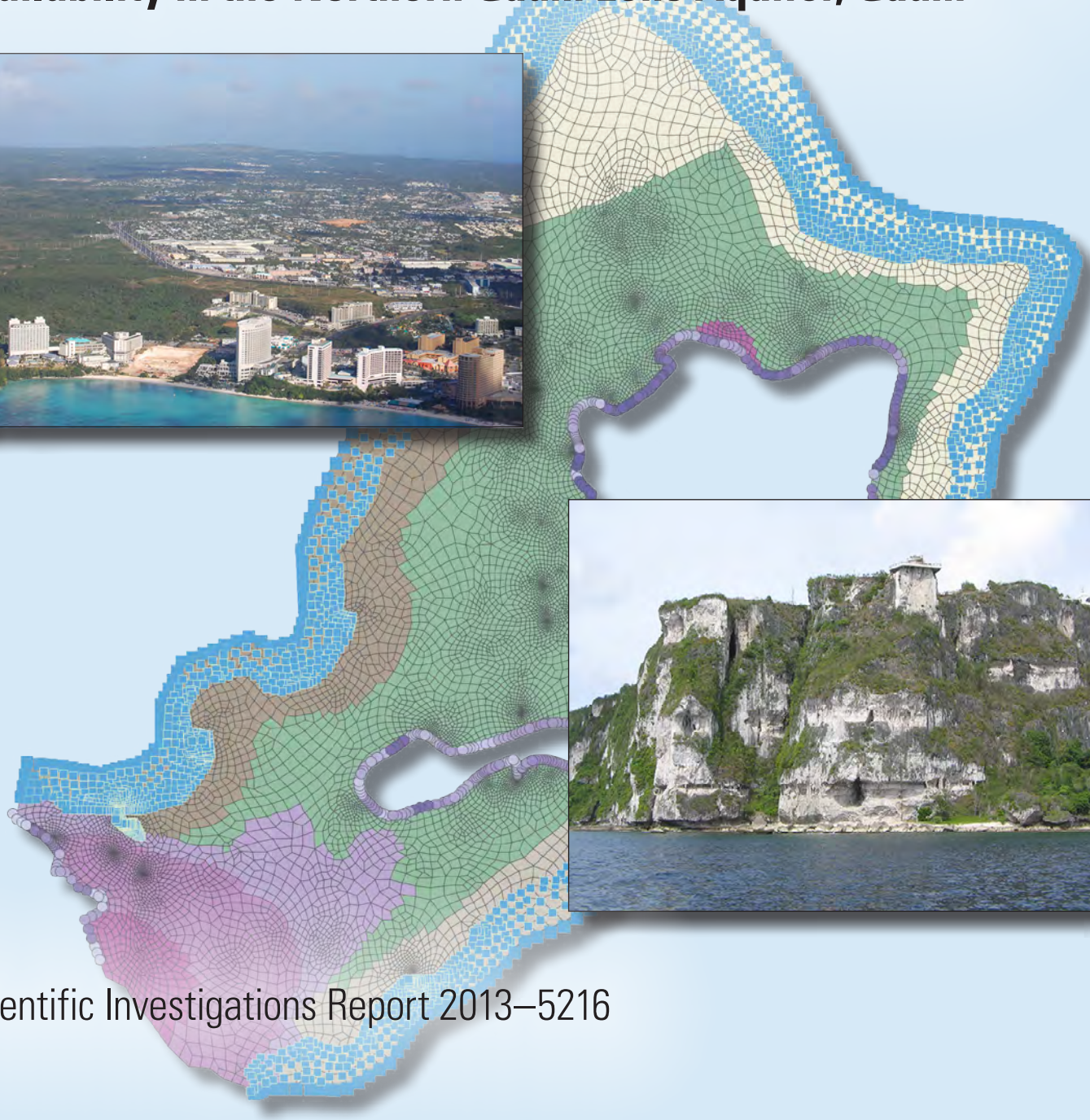
Prepared in cooperation with Headquarters, United States Marine Corps

The Effects of Withdrawals and Drought on Groundwater Availability in the Northern Guam Lens Aquifer, Guam



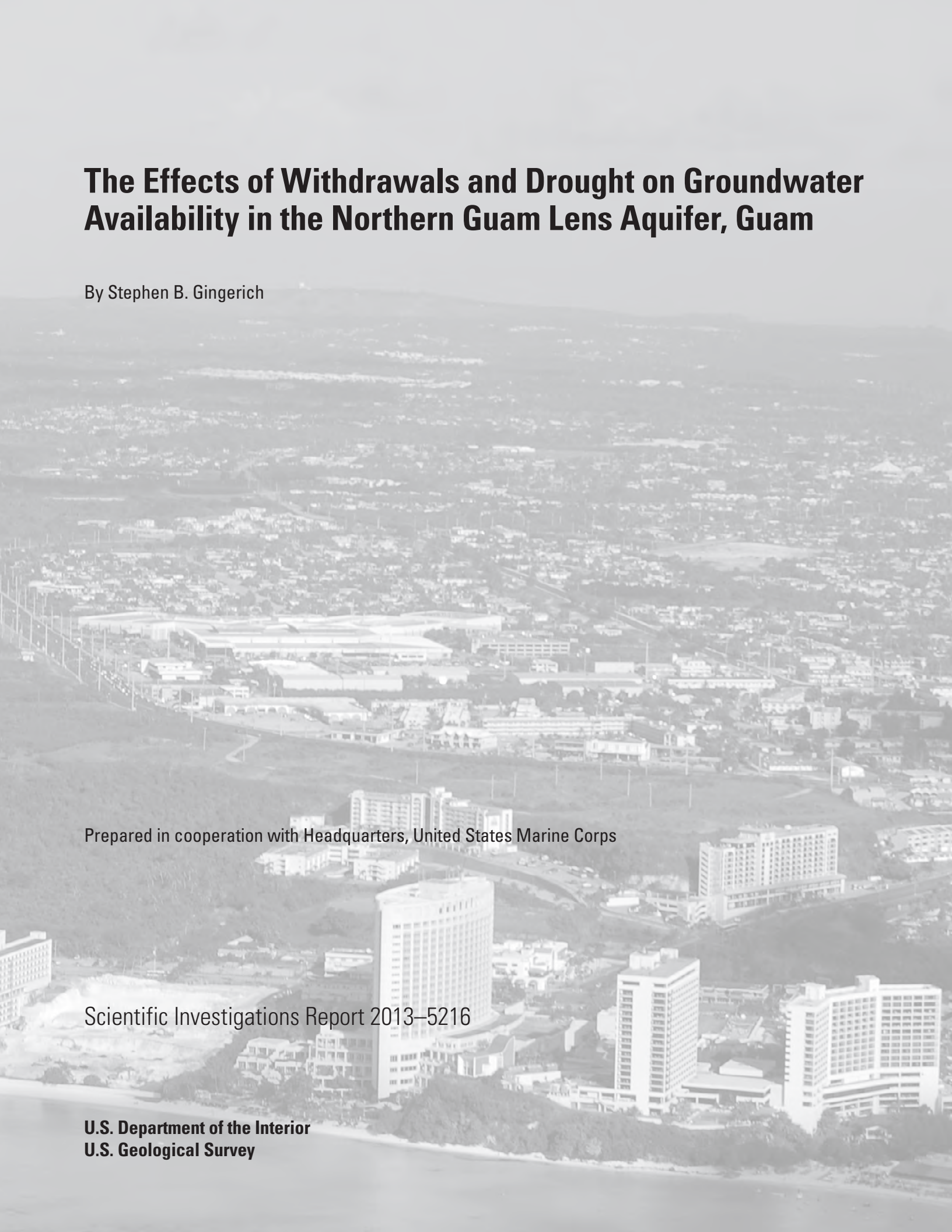
Scientific Investigations Report 2013–5216

U.S. Department of the Interior
U.S. Geological Survey

Cover photographs. *Left:* Interior of the northern Guam plateau, looking northeast along the Yigo-Tumon trough from above Tumon Bay on Guam's northwest coast. Photograph by Danko Taboroši. *Right:* Dos Amantes Point, north of Tumon Bay, on the northwest coast of Guam. Built in the reef facies of the Pleistocene-age Mariana Limestone, the cliff face stands about 200 feet above sea level and shows the imprints of several past sea-level stillstands. Photograph by John Jenson. Both photographs from the University of Guam, Water and Environmental Research Institute of the Western Pacific.

The Effects of Withdrawals and Drought on Groundwater Availability in the Northern Guam Lens Aquifer, Guam

By Stephen B. Gingerich



Prepared in cooperation with Headquarters, United States Marine Corps

Scientific Investigations Report 2013–5216

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this information product, for the most part, is in the public domain, it also may contain copyrighted materials as noted in the text. Permission to reproduce copyrighted items must be secured from the copyright owner.

Suggested citation:
Gingerich, S.B., 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, 76 p., http://dx.doi.org/10.3133/sir20135216.

ISSN 2328-0328 (online)

Executive Summary

Most of the public water supply on Guam is pumped from a freshwater lens in the Northern Guam Lens Aquifer, a limestone aquifer. Because of population growth and a potential military realignment involving the U.S. Marine Corps (USMC), groundwater withdrawals from wells are expected to increase. Currently (2013), the salinity of water pumped from some wells in the area is higher than acceptable for drinking water. The expected increase in demand for water has led to concern over the long-term sustainability of withdrawals from existing and proposed wells. In 2010, to aid in management of groundwater resources and to plan for sustainable growth on the island, the United States Marine Corps, Headquarters entered into a cooperative agreement with the U.S. Geological Survey (USGS) to study groundwater availability in northern Guam. The objective of this 3.5-year study was to estimate the effects of several hypothetical withdrawal scenarios on water levels, the transition zone between freshwater and saltwater, and salinity of pumped wells.

On Guam, freshwater-lens systems are found in limestone and volcanic rocks, but the most important groundwater sources are from the freshwater parts of these systems in the high-hydraulic-conductivity limestone rocks of northern Guam. The most intensely developed groundwater system in this area comprises a lens-shaped freshwater body, an intermediate brackish-water transition zone, and underlying saltwater. For management purposes, the Guam Environmental Protection Agency (GEPA) delineated the Northern Guam Lens Aquifer (NGLA) into six hydrologically connected aquifer basins: Agafo Gumas, Andersen, Finegayan, Hagåtña, Mangilao, and Yigo-Tumon.

Hydrologic Data

Knowledge of the NGLA hydrology comes from compilation and analysis of data on water levels, salinity profiles in deep monitoring wells, production well pumping rates and salinities, and geologic information gleaned from decades of well drilling and hydrologic monitoring. The NGLA Database (Bendixson, 2013) developed as part of this study but published separately, is the comprehensive collection of available hydrologic and geologic data. The data available from the NGLA Database is the foundation for the basement topography map (also developed as part of this study and published separately [Vann and others, 2013]) and the hydrologic concepts and subsequent numerical model developed for this report.

Groundwater Recharge and Discharge

Recharge to the NGLA from rainfall, irrigation, leaky water mains, and septic systems was estimated in this study to be about 238 million gallons per day (Mgal/d). Estimated recharge during a 5-year drought was 32 percent lower. Discharge from the aquifer in the study area occurs as withdrawals from wells, coastal springs, diffuse seepage to the ocean, and minor discharge to the Hagåtña Swamp. Average withdrawals from wells in 2010 totaled about 40 Mgal/d, about 36 Mgal/d by the Guam Water Authority (GWA) and 4 Mgal/d by the U.S. Navy and Air Force (hereafter referred to as Department of Defense [DoD]). Groundwater discharge to the ocean bordering the NGLA is estimated to be about 196 Mgal/d.

Numerical Groundwater Model

A three-dimensional numerical groundwater model capable of simulating density-dependent solute transport was developed as part of this study. The model was calibrated to steady-state conditions of 2010, using the USGS SUTRA code. Simulated water levels, the salinity of pumped water, and salinity profiles (values of salinity relative to depth) generally were in agreement with measured water levels, pumped-water salinities, and salinity profiles from representative wells in the modeled area during average conditions.

Future Withdrawal and Recharge Scenarios

The calibrated groundwater model was used to simulate changes in water levels and salinity under several hypothetical withdrawal and recharge scenarios. Simulated salinities at selected GWA and DoD wells are classified, for the purposes of this study, as acceptable if they are below about 200 milligrams per liter (mg/L) chloride concentration (about 1 percent seawater salinity), cautionary if they are between 200 and 500 mg/L chloride concentration (1.0 and 2.6 percent seawater salinity), and threatened if they are greater than 500 mg/L chloride concentration (about 2.6 percent seawater salinity). These categories are characterized around the secondary drinking water standard for chloride of 250 mg/L (Guam Environmental Protection Agency, 2001). Water in the acceptable category is expected to be below the standard, water in the cautionary category is near or above the standard but could be blended with fresher water to meet the standard, and water in the threatened category is well above the standard. Future recharge estimates are based on either historical average climate conditions or drought rainfall conditions and do not include potential effects of climate change on rainfall amounts or distribution.

In general, the freshwater lens gets smaller when withdrawal increases or recharge is reduced during drought. Groundwater withdrawal scenarios included no withdrawal, withdrawal at 2010 rates, reduced withdrawal during drought, and increased withdrawal for selected growth projections. Proposed withdrawal amounts and locations were based on input from the DoD and GWA.

Simulation results indicate that current conditions in the NGLA are different relative to conditions before any groundwater development in the following ways:

- water levels are more than 5 feet lower and the freshwater lens is more than 50 feet thinner in the southern part of the Hagåtña basin,
- water levels are up to 1 foot lower and the freshwater lens is thinner by 10–50 feet in most areas of the Yigo-Tumon basin,
- the freshwater lens is about the same size in the Agafo Gumas basin, and
- the zone of para-basal water (freshwater in the limestone above volcanic rocks) shifted as much as 5,000 feet inland in the interior part of the Yigo-Tumon basin.

For a 5-year drought scenario in which recharge is reduced about 32 percent, wells throughout the NGLA get saltier and the amount of acceptable yield is reduced from about 34 Mgal/d to 11.5 Mgal/d. The Yigo-Tumon basin has the highest number of wells in the

cautionary and threatened categories. These wells recover to pre-drought conditions within 5 years after the return of average recharge conditions. Reducing withdrawal at the wells with highest salinity by about 8 Mgal/d during the drought scenario brought the acceptable yield to 13.3 Mgal/d and eliminated all wells in the threatened category.

Five scenarios were used to investigate the results of projected groundwater withdrawals and proposed wells on the hydrologic system. The five scenarios are

Scenario 1—projected rates and locations for public water supply (GWA) and DoD (excluding USMC) wells based on the most likely estimate of future conditions,

Scenario 2—the same conditions as scenario 1 but including the expected USMC buildup,

Scenario 3—redistributing the DoD (including USMC) withdrawal for scenario 2 to lower salinity in some wells,

Scenario 4—the same conditions as scenario 3 with a 5-year drought, and

Scenario 5—the same conditions as scenario 2 but redistributing DoD and GWA wells to lower salinity in some wells.

Results of Five Scenarios

Scenario 1—Projected withdrawals without the USMC buildup (44.8 Mgal/d) lead to 15 wells having chloride-concentration increases greater than 10 mg/L relative to 2010 conditions (12 in the Yigo-Tumon basin and 3 in the Finegayan basin).

Scenario 2—Projected withdrawals including the USMC buildup (46.9 Mgal/d) lead to 17 wells having chloride-concentration increases greater than 10 mg/L relative to scenario 1 (8 wells in the Finegayan basin and 9 wells in the Agafo Gumas basin), and salinity from 3 wells increases from the acceptable to the cautionary salinity category.

Scenario 3—Redistributing the withdrawal from the DoD wells in the previous scenario lowers the amount of cautionary yield by 0.28 Mgal/d and lowers the amount of threatened yield by 0.3 Mgal/d. Fourteen wells had chloride concentration increases greater than 10 mg/L relative to scenario 1 (4 wells in the Finegayan basin and 10 wells in the Agafo Gumas basin).

Scenario 4—A 5-year drought with scenario 3 withdrawal rates leads to the majority of wells having chloride concentration increases greater than 10 mg/L and the amount of acceptable yield being reduced to only 8.94 Mgal/d.

Scenario 5—Redistributing rates at DoD and GWA wells to maximize withdrawal and maintain acceptable salinities at DoD and GWA wells allows 46.51 Mgal/d of withdrawal, 38.38 Mgal/d with acceptable salinity and 8.13 Mgal/d with cautionary salinity.

The numerical model developed for this study simulates water levels and salinity on a regional scale and thus may not accurately predict either the pumped water level at an individual well or the salinity of water pumped from that well, but these values are still indicative of expected regional trends in water levels and salinity. Salinity of water pumped from a well may be controlled by local heterogeneities in the aquifer that are not represented in the model. Model reliability can be improved as the understanding of groundwater recharge, the distribution of the aquifer hydraulic values, and the geometry of the hydrologic features become better known through additional data collection, compilation, and analysis. Together, a numerical model and an ongoing comprehensive monitoring program can provide managers and regulators with the means for sustainable management of future groundwater production. Sustainable management includes improving the efficiency of production and delivery as the resource use expands, managing demand for the resource, supplying different levels of quality and quantity to meet different demands for different uses, and promoting conservation and efficiency of use.

Acknowledgments

This study was funded through a cooperative agreement between Headquarters, United States Marine Corps and the U.S. Geological Survey (USGS). The USGS in turn engaged the University of Guam's Water and Environmental Research Institute of the Western Pacific (WERI), with whom it has had a longstanding collaborative relationship, to provide local scientific expertise and coordinate with local cooperating agencies in developing a well database and volcanic basement map to support the study, mainly through the efforts of Dr. John Jenson and Vivianna Bendixson. Other members at WERI whose contributions are greatly appreciated include Dr. Gary Denton, Dr. Shahram Khosrowpanah, Nathan Habana, and Christine Simard. Travis Hylton, Kay Chang, and Kevin Oshiro of NAVFAC Pacific helped frame the scenarios and gather pumping information; and Brett Railey and Martin Roush of Guam Waterworks Authority (GWA) and the late Benny Cruz (Guam Environmental Protection Agency) also provided data and suggestions for the study. David Vann provided updates on the volcanic basement map. Adam Johnson of the USGS Pacific Islands Water Science Center completed the recharge study that was an important component to this groundwater availability study. Dr. Kolja Rotzoll of the University of Hawai‘i Water Resources Research Center worked closely with the author and Dr. John Jenson to evaluate the water-level data and determine aquifer properties. The author also wishes to thank the numerous attendees of the technical advisory meetings throughout the project for feedback and suggestions. Participating agencies included WERI, GWA, the U.S. Navy and Air Force (hereafter referred to as the Department of Defense [DoD]), Guam Environmental Protection Agency (GEPA), U.S. Environmental Protection Agency, the Consolidated Commission on Utilities, and several private consulting firms. Todd Presley of the USGS provided support in resurveying measuring points and collecting valuable water-level data during the study.

This page left intentionally blank

Contents

Executive Summary iii
Hydrologic Data iii
Groundwater Recharge and Discharge iii
Numerical Groundwater Model iv
Future Withdrawal and Recharge Scenarios iv
Results of Five Scenarios v
Acknowledgments vii
Abstract 1
Introduction 1
Setting 2
Land Cover 2
Climate 4
Geology 4
Hydraulic Properties of the Rocks 8
Hydraulic Conductivity 8
Specific Storage and Effective Porosity 10
Dispersion 10
Groundwater Flow System 10
Freshwater Lens 10
Recharge 12
Discharge 12
Withdrawals From Wells 12
Coastal Springs 14
Water Levels 14
Salinity 17
Simulation of Groundwater Flow 21
Model Construction 21
Model Mesh 21
Boundary Conditions 21
Specified-Pressure and No-Flow Boundaries 21
Recharge 23
Withdrawal 23
Water Properties 23
Aquifer Properties 23
Simulated Average Conditions 26
Water Levels 26
Salinity in Wells 33
Pumped Wells 33
Salinity Profiles 33
Coastal Discharge of Fresh Groundwater 36
Groundwater Conditions Before Pumping 36
Drought Conditions 42

Drought Conditions With Reduced Withdrawal 49
Simulated Future Scenarios....49
Scenario 1—2010–11 Withdrawal Rates and Locations Plus Expected GWA and DoD (Excluding USMC) Growth With Average Recharge 55
Scenario 2—2010–11 Withdrawal Rates and Locations Plus Expected GWA and DoD (Including USMC) Growth With Average Recharge 56
Scenario 3—2010–11 Withdrawal Rates and Locations Plus Planned and USMC Growth (Redistributed) With Average Recharge 56
Scenario 4—2010–11 Withdrawal Rates and Locations Plus Planned and USMC Growth (Redistributed) With 5-Year Drought....57
Scenario 5—Redistributed 2010–11, Planned, and USMC Withdrawal Rates and Locations With Average Recharge 57
Model Sensitivity to Parameter Variability 63
Study and Model Limitations....63
Needs for Additional Study 64
Summary....65
References Cited....67
Appendix 1. Properties of wells in the numerical model of the Northern Guam Lens Aquifer, Guam....71

Figures

1. Location map and major physiographic areas of Guam 3
2. Mean annual rainfall and locations of selected rain gages and weather stations, Guam....5
3. Geologic map of Guam....6
4. Topography of the volcanic basement beneath the Northern Guam Lens Aquifer, Guam 7
5. Range of hydraulic-conductivity and specific-yield estimates and simulated distribution of regional aquifer hydraulic conductivity and specific yield based on observed tidal-signal attenuation and average water levels during 2010 in the Northern Guam Lens Aquifer, Guam 9
6. Schematic cross section of the study area showing groundwater occurrence and movement, Northern Guam Lens Aquifer, Guam 11
7. The distribution of mean annual groundwater recharge for baseline conditions on Guam calculated by using the water-budget model 13
8. Measured water levels during 2010 in selected wells in the Northern Guam Lens Aquifer, Guam 15
9. Average chloride concentration during 2000–10 in wells in the Northern Guam Lens Aquifer, Guam 18
10. Measured salinity profiles in selected monitoring wells (December 2009 or May 2010 [EX-8]), Northern Guam Lens Aquifer, Guam 19
11. Model discretization and features for the numerical groundwater model mesh of the Northern Guam Lens Aquifer, Guam....22

12. Selected withdrawal wells used in construction of the numerical groundwater model of the Northern Guam Lens Aquifer, Guam 24
13. Graph comparing measured and simulated water levels in selected wells in the Northern Guam Lens Aquifer, Guam 26
14. Measured and simulated water levels in selected wells in the Northern Guam Lens Aquifer, Guam 32
15. Relation between measured and simulated approximate chloride concentration in selected wells in the Northern Guam Lens Aquifer, Guam, by aquifer basin 34
16. Simulated salinity at pumped wells in the Northern Guam Lens Aquifer, Guam 37
17. Measured and simulated salinity profiles in selected monitoring wells in the Northern Guam Lens Aquifer, Guam 38
18. Simulated freshwater thickness in the Northern Guam Lens Aquifer, Guam 40
19. Simulated freshwater discharge from the Northern Guam Lens Aquifer, Guam 41
20. Simulated change (relative to predevelopment) for withdrawal at 2010 rates with long-term average recharge, Guam 43
21. Simulated change (relative to predevelopment) in salinity profiles in selected deep monitoring wells, Northern Guam Lens Aquifer, Guam 44
22. Simulated change (relative to predevelopment) in the position of the para-basal zone in the Northern Guam Lens Aquifer, Guam 46
23. Simulated salinity data for a hypothetical 5-year drought using 2010 pumping rates at selected wells in the Northern Guam Lens Aquifer, Guam 49
24. Difference in withdrawal at pumped wells relative to 2010 pumping rates in the Northern Guam Lens Aquifer, Guam 58
25. Simulated salinity at pumped wells in the Northern Guam Lens Aquifer, Guam 60
26. Simulated salinity difference at pumped drinking-water wells in the Northern Guam Lens Aquifer, Guam 61
27. Simulated salinity at pumped wells in the Northern Guam Lens Aquifer, Guam 62

Tables

1. Measured and simulated water levels in selected wells, Northern Guam Lens Aquifer, Guam 16
2. Aquifer-property values used in the construction of the numerical groundwater model of the Northern Guam Lens Aquifer, Guam 25
3. Recharge for selected simulations, Northern Guam Lens Aquifer, Guam 26
4. Selected wells and withdrawal rates used in calibration and drought scenarios, Northern Guam Lens Aquifer, Guam 27
5. Classification of withdrawal for simulated scenarios, Northern Guam Lens Aquifer, Guam 47
6. Selected wells and withdrawal rates used in future scenarios, Northern Guam Lens Aquifer, Guam 51

Conversion Factors, Abbreviations, and Datums

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Pressure	
pound per square foot (lb/ft^2)	0.04788	kilopascal (kPa)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Dynamic viscosity	
Slug per foot per second (slug/ft/s)	47.88	Pascal-sec (Pa-s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8× °C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

Vertical coordinate information is referenced to Guam Vertical Datum of 2004 (GUVD04) and is informally called mean sea level in this report.

Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS 84).

Elevation, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

The Effects of Withdrawals and Drought on Groundwater Availability in the Northern Guam Lens Aquifer, Guam

By Stephen B. Gingerich

Abstract

Owing to population growth, freshwater demand on Guam has increased in the past and will likely increase in the future. During the early 1970s to 2010, groundwater withdrawals from the limestone Northern Guam Lens Aquifer, the main source of freshwater on the island, tripled from about 15 to 45 million gallons per day. Because of proposed military relocation to Guam and expected population growth, freshwater demand on Guam is projected to increase further. The expected increased demand for groundwater has led to concern over the long-term sustainability of withdrawals from existing and proposed wells.

A three-dimensional numerical groundwater flow and transport model was developed to simulate the effects of hypothetical withdrawal and recharge scenarios on water levels and on the transition zone between freshwater and saltwater. The model was constructed by using average recharge during 1961–2005 and withdrawals from 2010. Hydraulic properties used to construct the model were initially based on published estimates but ultimately were adjusted to obtain better agreement between simulated and measured water levels and salinity profiles in the modeled area.

Two hypothetical groundwater withdrawal scenarios were simulated: no withdrawal to simulate predevelopment conditions and withdrawal at 2010 rates under a 5-year drought. Simulation results indicate that prior to pumping; the freshwater lens was 10 to 50 feet thicker in the Yigo-Tumon basin and more than 50 feet thicker in the Hagåtña basin. Results also indicate that continuing the 2010 withdrawal distribution during a 5-year drought would result in decreased water levels, a thinner freshwater lens, and increased salinity of water pumped from wells. The available water with an acceptable salinity (chloride concentration less than 200 milligrams per liter) would decrease from about 34 million gallons per day to 11.5 million gallons per day after 5 years but recover to pre-drought levels 5 years after the return of average recharge conditions.

Five additional scenarios were simulated to assess groundwater demand projections and proposed new well sites for the Department of Defense and Guam Water Authority wells under average and drought conditions. Simulation results from these projected withdrawal scenarios indicate decreased water levels, a thinner freshwater lens, increased water salinity, and unacceptable salinity at several current withdrawal sites. However, for the scenario including projected U.S. Marine Corps demands (46.62 million gallons per day, including 10 proposed wells) more than 40 million gallons per day of the withdrawn groundwater remains in the acceptable category. During a 5-year drought, this same pumping distribution results in only about 15 million gallons per day of withdrawn groundwater having acceptable salinity.

A scenario in which groundwater withdrawal was redistributed in an attempt to maximize withdrawal while maintaining acceptable salinities in the withdrawn water was simulated. The redistributed withdrawal simulates about 47 million gallons per day of withdrawal with more than 41 million gallons per day of withdrawal with acceptable salinity.

Introduction

Owing to population growth, freshwater demand on Guam has increased in the past and will likely increase in the future. During 1970–2010, the resident population on Guam grew from about 86,000 to 181,000 (U.S. Census Bureau, 2011). In addition, the tourist industry brings many visitors, and Guam hosted just over 1 million tourists in 2010 (Guam Visitors Bureau, 2010). During the early 1970s to 2010, groundwater withdrawals from the freshwater lens which is contained in the Northern Guam Lens Aquifer (NGLA), the main source of freshwater on the island, tripled from about 15 to 45 million gallons per day (Mgal/d) according to Mink (1976) and the U.S. Navy, Naval Facilities Engineering Command, Pacific (NAVFAC Pacific, 2010). In 2010, total freshwater demand on Guam was about 58 Mgal/d, with groundwater supplying nearly 80 percent of that demand (NAVFAC Pacific, 2010). By 2020, population growth on Guam is projected to add 23,000 people to the 2010 population (U.S. Census Bureau, 2011). In addition to this growth, a proposed military buildup in the near future includes the transfer of U.S. Marines and their dependents from Okinawa, Japan,

to Guam. Because of the military relocation and population growth, freshwater demand on Guam is projected to increase (NAVFAC Pacific, 2010). Those concerns led the Headquarters, U.S. Marine Corps (USMC) to enter into a cooperative agreement with the U.S. Geological Survey (USGS) to conduct a groundwater-availability study of northern Guam. The objectives of this 3.5-year study were to (1) advance the understanding of regional groundwater dynamics in the NGLA, (2) provide a new estimate of groundwater recharge for the entire island, and (3) develop a numerical groundwater flow and transport model for northern Guam that could serve as a tool to assist water-resource managers in estimating the effects of selected groundwater-pumping and climate scenarios on the water supply. Objective 2 was met with the prior publication of a USGS Scientific Investigations Report describing groundwater recharge estimates (Johnson, 2012). Objectives 1 and 3 are addressed in this report. This report describes (1) information related to the regional hydrologic system of the NGLA, (2) development of a numerical groundwater flow and transport model, and (3) results of model simulations assessing the hydrologic effects of various recharge and withdrawal conditions on the hydrologic system.

Setting

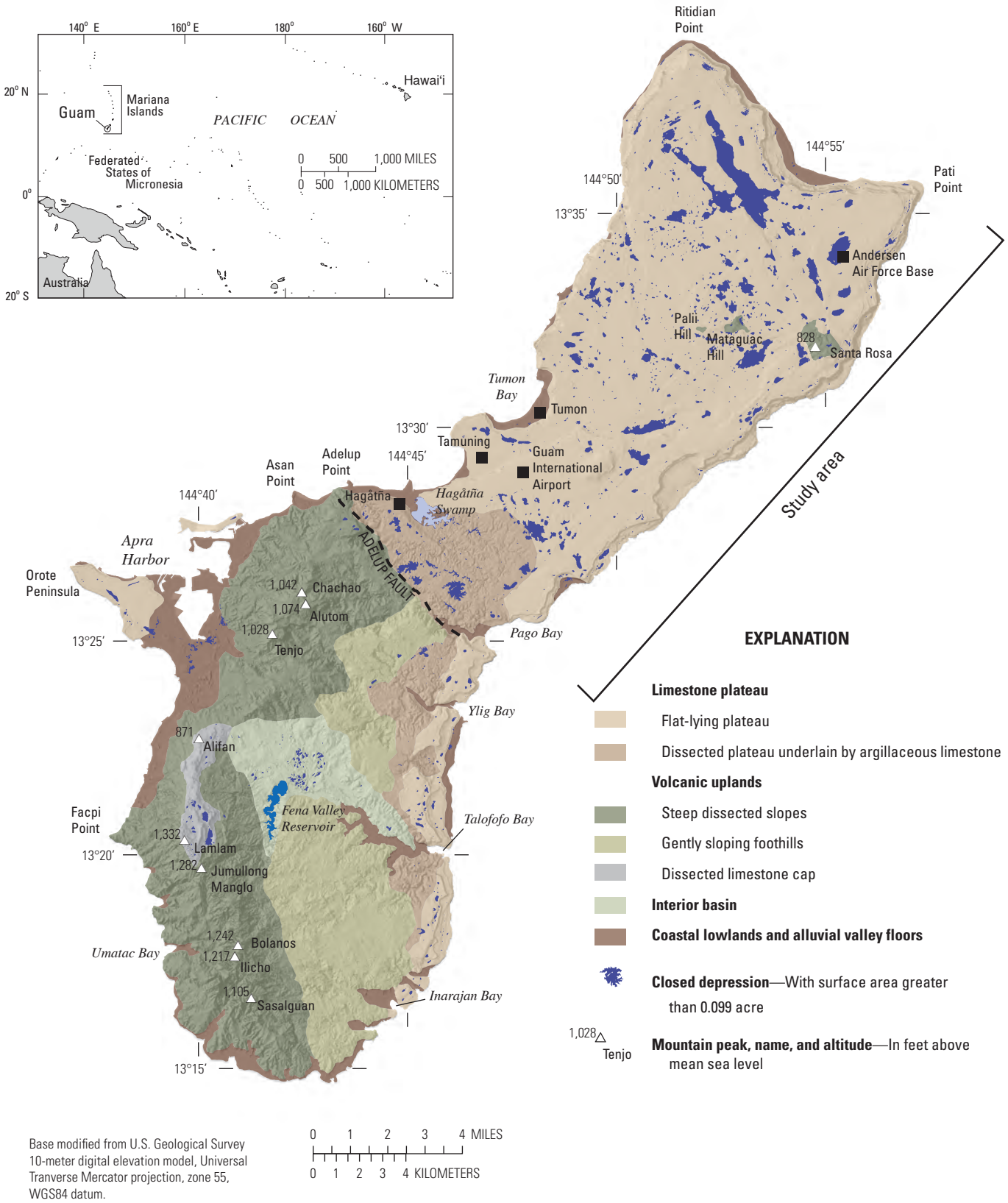
Guam, the largest and southernmost of the Mariana Islands, lies in the tropical western Pacific Ocean between latitude 13°14′N. and 13°40′N. and between longitude 144°37′E. and 144°58′E (fig. 1). The island is divided into northern and southern geographic provinces by the Adelup fault, which extends across the island's center from Pago Bay to Adelup Point. The land surface, 211 square miles (mi^2), consists of four major physiographic landforms: limestone plateau, volcanic uplands, interior basin, and coastal lowlands (Tracey and others, 1964; Young, 1988) (fig. 1).

As documented by Tracey and others (1964), the island's southern half is predominantly rugged volcanic uplands that have been cut by streams. A discontinuous ridge of mountains, with many peaks over 1,000 feet (ft) in altitude, extends from Mount Chachao to the island's southern tip. The highest point on Guam, Mount Lamlam at 1,332 ft, is on the narrow band of limestone that caps the volcanic uplands. Orote Peninsula is a limestone plateau up to 200 ft high that extends west of the southern province. East of the mountain ridgeline, the volcanic land surface is characterized by steep slopes at higher elevations and gently rolling hills at lower elevations. A partially incised limestone plateau fringes the east coast from Pago Bay to Inarajan Bay. The interior basin is a structural depression that extends inland from Talofofo Bay to the dissected limestone cap; it includes Fena Valley Reservoir, the dissected karst terrane northeast of Fena Valley Reservoir, and rolling hills and valleys comprising volcanic, limestone, and alluvial units.

The island's northern half is a broad limestone plateau bordered by steep cliffs and discontinuous coastal lowlands. Gently tilted to the southwest, the plateau slopes from an altitude of more than 600 ft in the north to less than 200 ft near the narrow center part of the island northwest of the Adelup fault (fig. 1). Volcanic rocks protrude through the limestone plateau at Mount Santa Rosa and Mataguac and Palii Hills. Except for cliffs, the slope of the land surface is generally less than 10 percent. Most of the plateau lacks stream channels, but it has many closed depressions. Near the southern volcanic uplands, however, the plateau is cut by drainage channels that funnel runoff into closed depressions and the Hagåtña Swamp.

Land Cover

According to the U.S. Department of Agriculture (2006) vegetation map, about 57 percent of the land surface of the northern Guam study area is covered by forests; most other areas are urbanized or are covered by grasslands. The study area contains most of the urbanized areas of the island, covering about 40 percent of the study area. U.S. Military lands cover about 25 percent of the study area. Owing to a long history of disturbances, (typhoons, World War II, and human development), little undisturbed primary forest exists on the island (Fosberg, 1960). Consequently, the forests on Guam are mostly dense, tangled thickets of weedy, secondary trees that surround scattered trees of taller stature (Fosberg, 1960). Forest land-cover categories "Limestone forest" and "Scrub forest" cover much of the undeveloped areas underlain by limestone. Dense thickets of *Leucaena leucocephala* (Fosberg, 1960) commonly cover disturbed areas within these forests. *L. leucocephala,* known to Guamanians as tangantangan, is estimated to be the most abundant tree species on Guam (Donnegan and others, 2004). In the island's southern half, the volcanic uplands are mostly covered by "Savanna complex" or "Ravine forest." Savanna complex is a mixed grassland dominated by *Miscanthus floridulus* (swordgrass), which grows in dense clumps up to 10 ft high (Fosberg, 1960). Ravine forest consists of trees, generally brushy and low in stature, which form a dense and irregular canopy (Fosberg, 1960). About 10 percent of Guam's land is used for agriculture, split evenly between the north and south.



Base modified from U.S. Geological Survey 10-meter digital elevation model, Universal Tranverse Mercator projection, zone 55, WGS84 datum.

Figure 1. Location map and major physiographic areas of Guam (modified from Tracey and others, 1964; Young, 1988).

Climate

The source of all freshwater on Guam is rainfall. Seasonal differences in rainfall and wind define the distinct wet and dry seasons. Across the northern plateau, about one-third of the annual precipitation falls during the dry season months (January through June) and about two-thirds during the wet season months (July through December) (Lander and Guard, 2003). During the dry season, northeasterly trade winds are persistent, and most rain falls as light showers in amounts typically no more than 0.25 inch (in.) per day (Lander and others, 2001). Mean rainfall across the island is less than 8 in. per month during the dry season. During the wet season, winds weaken and typically veer to the southeast, and the atmosphere over the island is more humid and unstable (Guard and others, 1999). As a result, rain predominantly originates convectively and falls as moderate to heavy downpours (Lander and others, 2001). Mean wet-season rainfall across the island ranges between 5 and 18 in. per month. Rainfall-producing weather systems during the wet season range in spatial scale from isolated thunderheads to weather systems that affect the entire island, including (1) clusters of convective clouds, (2) monsoon squall lines, and (3) convective clouds associated with the periphery or core of tropical cyclones (Lander and others, 2001). On average, about 30 percent of the wet season rainfall is induced by tropical cyclones (Kubota and Wang, 2009). Typhoon passage near or directly over the island can produce torrential downpours with rainfall rates exceeding 6 in. per hour and 20 in. per 24 hours (Lander and Guard, 2003).

Mean rainfall ranges from about 84 inches per year (in/yr) near Apra Harbor to about 116 in/yr in the southern highlands (Daly and Halbleib, 2006) (fig. 2). The largest deviations from mean rainfall conditions are related to tropical cyclones and El Niño/La Niña-Southern Oscillation events (Lander and Guard, 2003). Some of the wettest years have been during years when typhoons pass nearby or directly over the island (Lander and Guard, 2003). Rainfall during a year with El Niño conditions tends to be above average (Guard and others, 1999). Some of the driest years happened during the year following an El Niño event (Lander, 1994).

Geology

The following discussions on geology and hydraulic properties of rocks are extracted from Rotzoll and others (2013). Tracey and others (1964) first described Guam's geology in detail. Subsequently, Reagan and Meijer (1984) reclassified some of the volcanic rock units, and Siegrist and Randall (1992) reinterpreted some of the limestone units. Siegrist and Reagan (2007) accordingly updated the original map (Tracey and others, 1964) (fig. 3) and the geologic names used in this report are based on their descriptions. The basement beneath the NGLA is the Late Eocene to Early Oligocene Alutom Formation (Tracey and others, 1964). The Alutom Formation constitutes the second-oldest exposed volcanic rock unit on Guam, overlying the Late Middle Eocene Facpi Formation (Reagan and Meijer, 1984), which forms the island's basement. Age determinations of Guam geologic units are based mainly on fossil remains and correlations with other islands in the Pacific.

The Alutom Formation is estimated to be 1,850–2,000 ft thick (Reagan and Meijer, 1984; Siegrist and Reagan, 2007). Basement rocks occupy less than 1 percent of Guam's northern surface. However, about 20 percent of the basement topography stands above modern sea level (Mylroie and others, 2001). Vann and others (2013) recently published a topographic map of the volcanic basement updated by use of well logs and geophysical data (fig. 4). Under vadose conditions, systems of conduit caves form along the contact of the limestone bedrock and underlying basement. The Alutom Formation is composed mostly of water-lain pyroclastic rocks ranging from tuffaceous shale to coarse boulder conglomerate and breccia. The generally fine-grained texture and poor sorting of the volcaniclastic Alutom basement rock give it much lower hydraulic conductivity than the limestone bedrock (Ward and others, 1965); thus, the basement is considered to be the lower boundary of the aquifer. A locally important argillaceous limestone unit, the Janum Limestone, exposed on the northeastern coast, reflects the local deposition of siliciclastic sediments descending from the flanks of the weathered Alutom volcanic rocks, producing a "dirty" limestone apron.

The surface of Guam's northern plateau is composed almost entirely of Miocene to Pleistocene limestone bedrock overlying the Alutom Formation (fig. 3). Within the plateau, the Barrigada Limestone, of Late Miocene to Pliocene age, forms the bulk of the aquifer, although it is exposed on only 18 percent of the surface. It consists of fine-grained, pure foraminiferal-detrital limestone, which grades upward and outward into the overlying Mariana Limestone (Ward and others, 1965; Contractor and Srivastava 1990; Jocson and others, 2002). With a thickness of greater than 540 ft (Camp, Dresser & McKee Inc., 1982; Tracey and others, 1964), the permeable and productive Barrigada Limestone supplies water to most of the wells in northern Guam.

Occupying about 65 percent of Guam's northern surface and nearly all of the periphery of the plateau, the Pliocene- to Pleistocene-age Mariana Limestone is composed of reef and lagoonal sediments containing a wide range of lithologies (Tracey and others, 1964). The formation is thickest around the plateau perimeter. It thins to zero inland (fig. 3), where the underlying Barrigada Limestone has been exposed by downward erosion and removal of the Mariana lagoonal sediments that presumably covered it before the plateau was subaerially exposed by tectonic uplift beginning about 2 million years ago.

At the plateau's southern end, near the older volcanic uplands, the Mariana Limestone is clay-rich and may be underlain in substantial areas by the strongly indurated and denser Miocene Alifan Limestone. This part of the surface is mapped as the Hagåtña Argillaceous Member of the Mariana Limestone, hereafter called the "Argillaceous Limestone," and

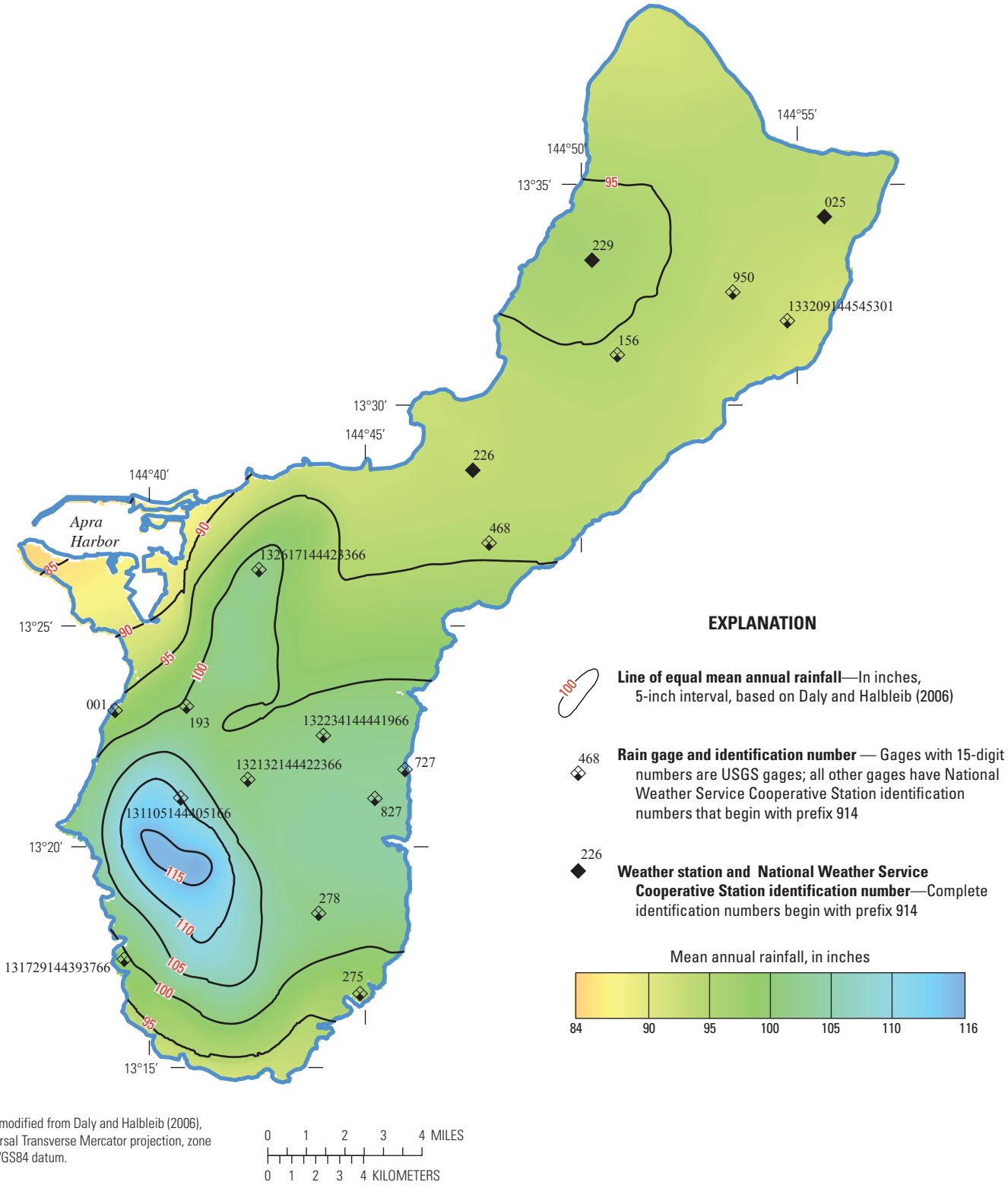
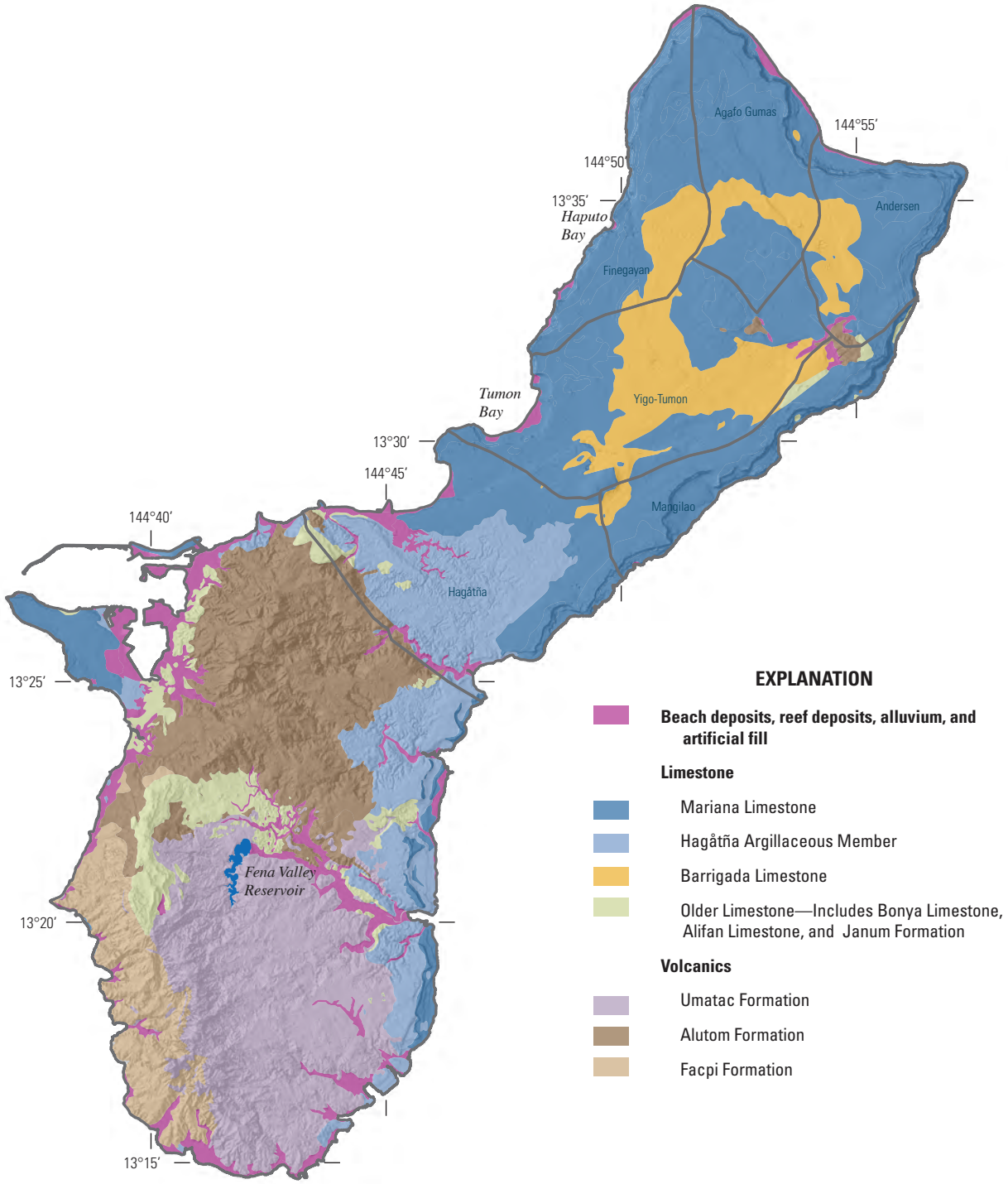


Figure 2. Mean annual rainfall and locations of selected rain gages and weather stations, Guam.



Base modified from U.S. Geological Survey 10-meter digital elevation model, Universal Tranverse Mercator projection, zone 55, WGS84 datum.

Figure 3. Geologic map of Guam (modified from Tracey and others, 1964; Siegrist and Reagan, 2007). Geologic nomenclature from Siegrist and Reagan (2007). Boundaries of named aquifer basins, as defined by Camp, Dresser & McKee, Inc. (1982), are shown in gray with names shown in blue.

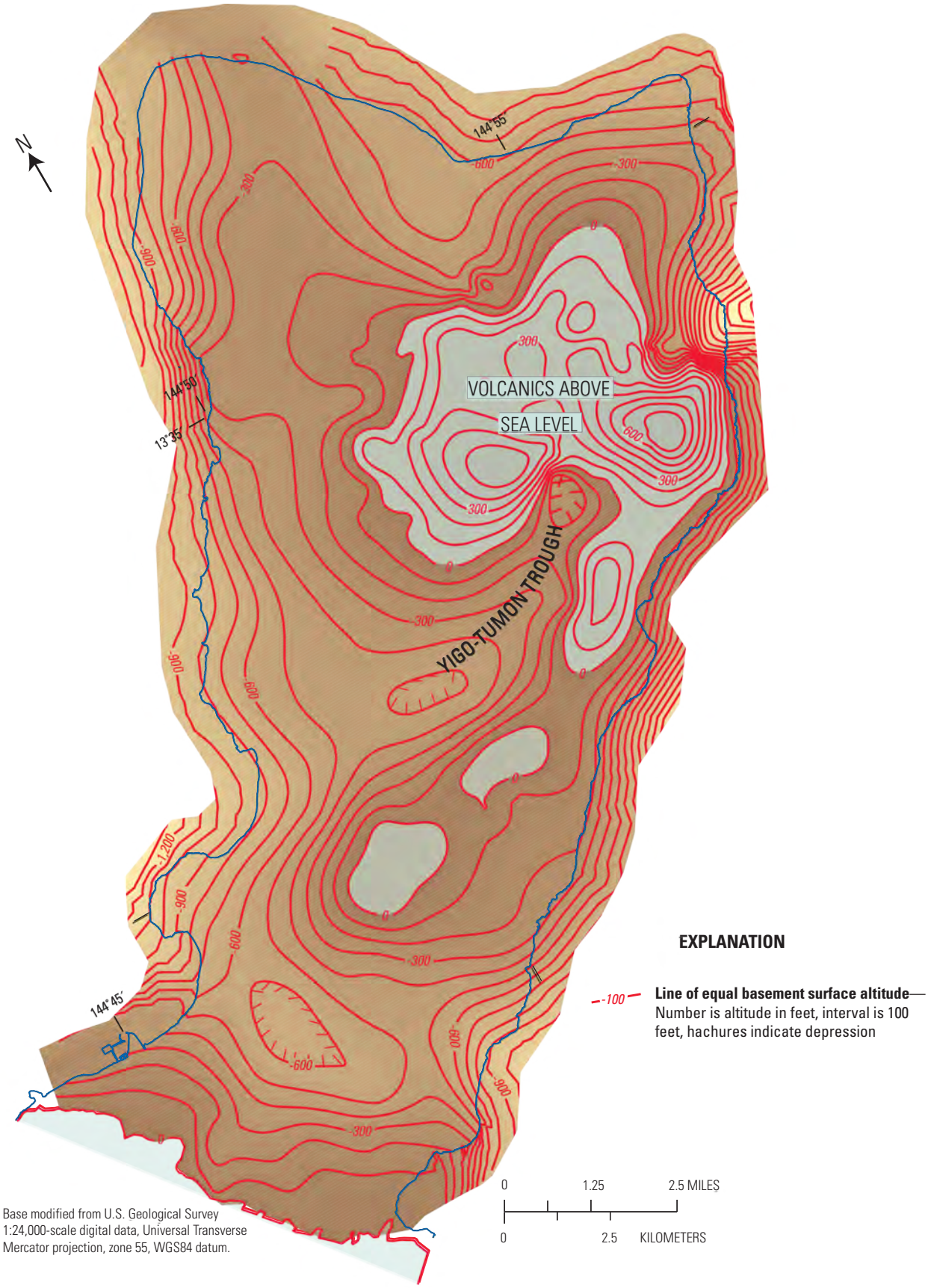


Figure 4. Topography of the volcanic basement beneath the Northern Guam Lens Aquifer, Guam (modified from Vann and others, 2013).

covers about 12 percent of northern Guam. Patches of surficial sediments, including beaches, alluvium, and artificial fill, and modern reef are of Holocene age, cover about 4 percent of Guam's northern surface, mostly along the periphery, and are locally significant in Tumon Bay and Haputo Bay (fig. 3) (Taboroši and others, 2009, 2013).

Hydraulic Properties of the Rocks

Hydraulic Conductivity

Hydraulic conductivity is a quantitative measure of a rock's capacity to transmit water. Hydraulic conductivity is the constant of proportionality in Darcy's law, which relates specific discharge (discharge per unit area) to the hydraulic gradient:

$$v = -K(\mathrm{d}h/\mathrm{d}l) , \quad (1)$$

where

v = specific discharge [LT^{-1}],
K = hydraulic conductivity [LT^{-1}], and
$\mathrm{d}h/\mathrm{d}l$ = hydraulic gradient [LL^{-1}].

Darcy's law generally is assumed applicable to regional groundwater flow analyses in Guam (Contractor, 1983; Contractor and Srivastava, 1990; Jocson and others, 1999; Contractor and Jenson, 2000).

Rock hydraulic conductivity describes the ease with which fluid can move through porous materials. Limestone hydraulic conductivity is variable and depends on many factors, including the mode of emplacement and amount of weathering. The geologically young, eogenetic limestone of northern Guam generally has high hydraulic conductivity (Ward and others, 1965; Vacher and Mylroie, 2002). Faults transecting the plateau complicate the structure and regional hydraulic conductivity of the aquifer rock units (Mylroie and others, 2001; Jenson and others, 2006). In previous modeling studies, the regional horizontal hydraulic conductivity of the main limestone aquifer generally is estimated to be thousands to tens of thousands of feet per day (Contractor and Srivastava, 1990; Jocson and others, 1999; Contractor and Jenson, 2000). Ayers and Clayshulte (1984) made regional hydraulic-conductivity estimates ranging from 3,300–19,700 feet per day (ft/d) from analyses of tidal-induced fluctuations in five wells of varying distances inland on the central west coast of northern Guam, and they noted "shoreline rocks may be lower in hydraulic conductivity," acting "as a dam to the inland propagating tidal signal."

Rotzoll and others (2013) analyzed tidal-signal attenuation in water-level records from 34 wells across northern Guam by means of an analytical solution and a numerical model (used as the starting point for the numerical model presented in this report) to estimate hydraulic diffusivity and conductivity. The results indicate a significant tidal-damping effect around the entire periphery of the aquifer where hydraulic diffusivities in wells near the island's periphery are two orders of magnitude lower than for wells in the island's interior. They presented a range of possible combinations of aquifer specific yield and thickness that could be used to estimate hydraulic conductivity from the hydraulic-diffusivity estimates (fig. 5). Using their numerical model, they then estimated hydraulic conductivities ranging from about 1,050 to 3,200 ft/d for peripheral areas and about 49,000 ft/d for interior areas. The Argillaceous Limestone unit underlying much of Hagåtña basin exhibits lower conductivity, ranging from 26 to 1,800 ft/d. A small area of low-conductivity rocks in the Agafo Gumas basin along the northern flank of the volcanic rocks is assumed on the basis of observed water levels greater than 30 ft. However, the high head in this area has yet to be definitively explained (AECOM Technical Services, Inc., 2011). The lower conductivity of the peripheral rocks relative to the interior rocks may best be explained by the effects of karst evolution: (1) dissolutional enhancement of horizontal hydraulic conductivity in the interior, with (2) case-hardening and concurrent reduction of local hydraulic conductivity in the cliffs and steeply inclined rocks of the periphery (Tracey and others, 1964) and (3) the stronger influence of higher-conductivity regional-scale features in the interior relative to the periphery (Rotzoll and others, 2013).

Rotzoll and others (2013) also demonstrated that the discontinuous ridge containing the Barrigada and Adacao Rise and the Santa Rosa Ridge along the southeast boundary of the Yigo-Tumon trough forms an effective hydrologic boundary between the east coast and the Yigo-Tumon wells, and the observed tidal data could not be reproduced by treating the ridge as discontinuous. No drill-hole data are available to confirm whether the ridge is discontinuous or not. Vann and others (2013) marked their interpretation of the ridge as discontinuous, with a question mark to highlight that their interpretation is not unique.

In general, the regional vertical hydraulic conductivity in the highly permeable parts of the aquifer may be tens to hundreds of times less than the horizontal hydraulic conductivity, owing to the depositional environment in which the limestone formed and postdepositional changes in porosity. Vacher and Mylroie (2002) suggest that conductivity increases by orders of magnitude as secondary pathways are connected by dissolution while vertical conductivity decreases as original matrix porosity is occluded. Because most of the Barrigada Limestone is very fine-grained foraminiferal deposits that accumulated in a relatively deepwater environment, some natural anisotropy likely also developed through deposition. However, no direct measurements or estimates of the vertical hydraulic conductivity of the NGLA are available. Anisotropy between vertical and horizontal hydraulic conductivity in other types of young carbonate aquifers is well established; numerical modeling studies of carbonate atoll islands have used ratios of horizontal to vertical hydraulic conductivity ranging from 5:1 to 12:1 (Peterson and Gingerich, 1995; Bailey and others, 2009).

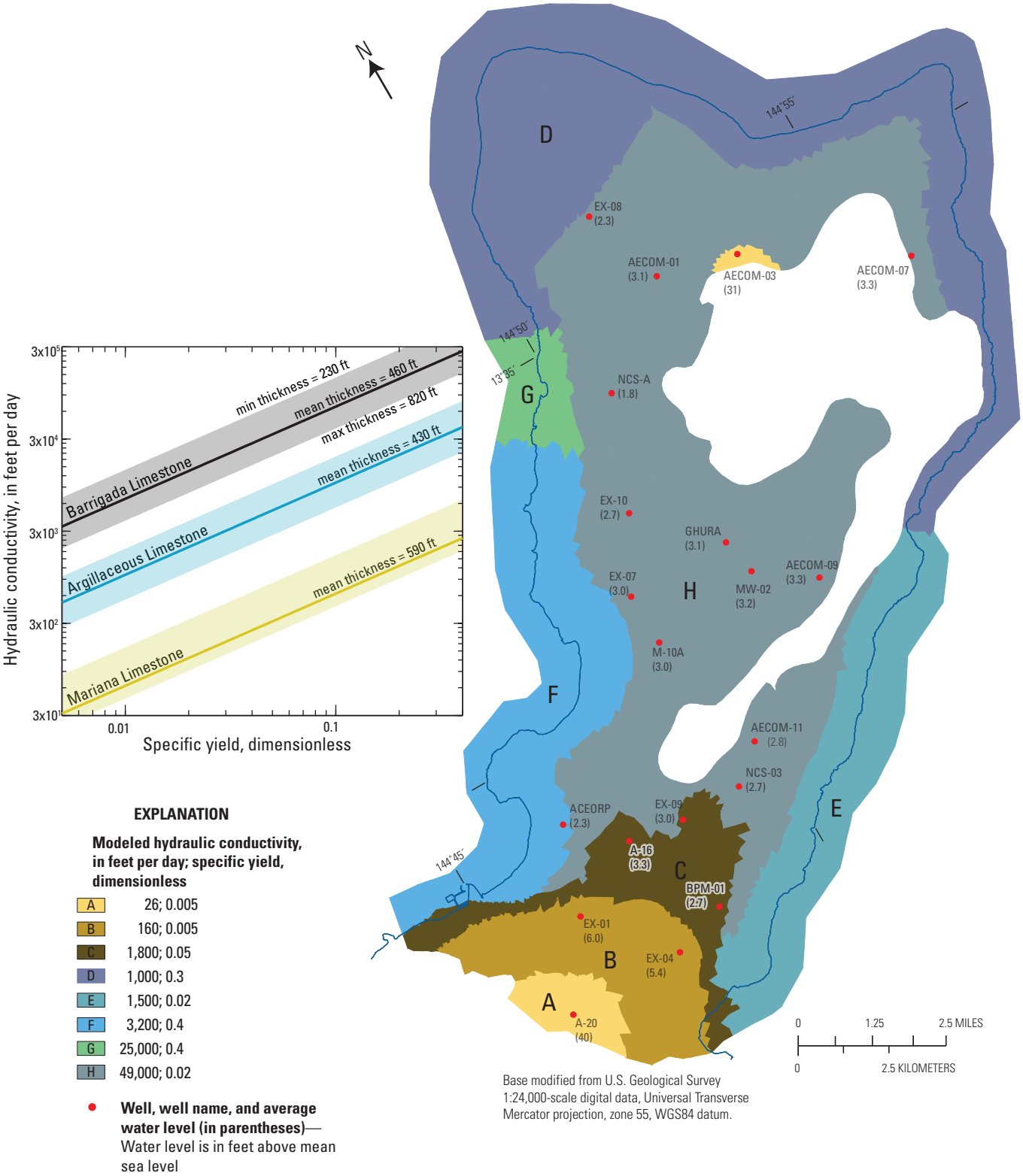


Figure 5. Range of hydraulic-conductivity and specific-yield estimates and simulated distribution of regional aquifer hydraulic conductivity and specific yield based on observed tidal-signal attenuation (modified from Rotzoll and others, 2013) and average water levels during 2010 in the Northern Guam Lens Aquifer, Guam.

Specific Storage and Effective Porosity

The effective porosity and specific storage of the rocks forming an aquifer affect the timing and amount of the water-level response to natural or human-induced changes. Total rock porosity is the ratio of the volume of void spaces to the total rock volume. The effective porosity represents that part of the total rock porosity that contributes to flow, and specific storage is a measure of the compressive storage of the rocks and fluid. Small effective-porosity or specific-storage values result in relatively rapid and larger water-level changes in response to changes in pumping or recharge, whereas large effective-porosity or specific-storage values result in relatively slower and smaller water-level changes.

As summarized by Rotzoll and others (2013), dye-trace studies have shown that the NGLA is a multiple-porosity aquifer, with substantial but variable contributions from residual primary porosity, dissolution porosity, pervasive fracture porosity, and locally important conduit porosity (Andersen Air Force Base Environmental Review, 1995; Barner 1995, 1997; Moran and Jenson, 2004). Given that the upper 300 ft of the modern phreatic zone was part of the vadose zone throughout most of the Pleistocene and that the freshwater lens migrated up and down through this vertical section several times during successive glaciations, the porosity and "plumbing" of the limestone aquifer have been profoundly affected by vadose and phreatic freshwater diagenesis and karst dissolution, with consequent redistribution of porosity and cementation (Longman, 1980; Vacher and Mylroie, 2002).

A gravity survey over the Mariana Limestone surface showed an average density of 146.7 pounds per cubic foot (lb/ft^3) which, assuming that the limestone is entirely calcite, indicates a regional total porosity of 0.08 to 0.17, with a mean of 0.13 (Camp, Dresser & McKee Inc., 1982; Mink and Vacher, 1997). Ayers and Clayshulte (1984) examined drill core and thin sections, including a continuous 500-ft core from the Barrigada Limestone in the island's interior, which penetrated the freshwater lens, noting that "by far the most abundant porosity type can be classified as vug porosity or moldic porosity," and that locally, "channel porosity may be the dominant type, particularly near the water table." (Vugs and molds are void spaces in the limestone created through the dissolution of a preexisting constituent of a rock, such as a shell, rock fragment, or grain.) They noted that in thin sections from the Argillaceous Limestone, "porosity was relatively low, generally less than 0.04." On the other hand, thin section porosity from the 500-ft core showed an average of 0.13 above the water table and 0.21 below it. These observations indicate that the original porosity in the NGLA, especially near the water table, has been strongly altered by dissolution and probably enhanced in the direction of groundwater flow, consistent with the "touching-vug" model of porosity evolution for eogenetic karst proposed by Vacher and Mylroie (2002).

For the purposes of the numerical modeling presented in this report, effective porosity is considered equal to specific yield. Specific-yield estimates from tidal-signal attenuation analyses range between 0.005 and 0.4 (Rotzoll and others, 2013) (fig. 5). The highest specific-yield estimates are associated with the lower hydraulic conductivity limestone units around much of the island's northern periphery. The lowest values are associated with the Argillaceous Limestone, for which hydraulic-conductivity values are lowest.

Dispersion

Mixing of freshwater with underlying saltwater in an aquifer creates a brackish-water transition zone. The extent of mixing in an aquifer depends on several factors including the groundwater velocity and the aquifer dispersivity. High dispersivity values, all other factors being equal, result in greater mixing. Dispersivity values generally are larger in the (longitudinal) direction of flow relative to directions transverse to flow and may be controlled by aquifer anisotropy. No reported dispersivity values are available for Guam. Numerical modeling studies of high-hydraulic-conductivity volcanic rock aquifers in Hawai'i used longitudinal transverse dispersivity values in the range of 250 ft for flow in the direction of maximum velocity and 25 ft for a minimum direction (Oki, 2005; Gingerich, 2008; Gingerich and Engott, 2012). Transverse dispersivity values typically range from 0.18 to 3.3 ft.

Groundwater Flow System

Fresh groundwater moves mainly from inland recharge areas to coastal areas where springs and seeps discharge above and below sea level. Flowing water from inland locations in northern Guam flows outward to discharge areas along the coast.

Freshwater Lens

On oceanic islands such as Guam, freshwater commonly forms a water body called a freshwater lens that floats on saltwater and is separated from the saltwater by a brackish-water transition zone (fig. 6). The freshwater, brackish water, and saltwater are all part of the freshwater-lens system. Salinity in a freshwater-lens system is gradational, from an upper freshwater core through the underlying transition zone to saltwater. In some places, especially near the coast, where freshwater is extensively mixed with saltwater, brackish water may exist immediately below the water table.

Transition-zone thickness depends on the extent of mixing between freshwater and saltwater and is generally several tens of feet in northern Guam. Mixing in the transition zone results from pumping and possibly tidal fluctuations superimposed on the gravity-driven freshwater flow toward the shore. A saltwater-circulation system is present beneath the freshwater lens. Saltwater flows landward in the deeper parts of the aquifer, flows upward, and then mixes with seaward-flowing fresher water (fig. 6). This mixing creates the brackish-water

transition zone. For the purposes of this report, freshwater is considered water with less than 500 milligrams per liter (mg/L) chloride concentration or 2.6 percent seawater salinity; brackish water is considered water with salinity that ranges between greater than 2.6 percent to less than 100 percent seawater salinity. When recharge is constant and water is continuously pumped from the freshwater-lens system, water levels will decrease and the transition zone will rise until a new equilibrium is reached between the amount of recharge to the system and the amount of discharge to wells and the coast.

Under conditions of steady recharge, no pumping, and no sea-level variation, the lens would ultimately reach a fixed extent and thickness. In reality, rainfall is episodic and seasonal, and lens volume fluctuates naturally with time. Groundwater discharges continuously throughout the year, but the lens shrinks during extended dry periods when recharge diminishes or ceases, and it expands when recharge increases.

On Guam, freshwater-lens systems are found in limestone and volcanic rocks, but the most important groundwater sources are from the freshwater parts of these systems in the high-hydraulic-conductivity limestone rocks of northern Guam (fig. 3). In the limestone with the highest hydraulic conductivity, the Barrigada Limestone, the water table is no more than a few feet above sea level, and the water-table slope is nearly flat. The freshwater lens in these rocks is relatively thin and is commonly called "basal" water after similar occurrences in Hawai'i (Meinzer, 1930). Wells and springs in this part of the system generally have water-level altitudes less than 7 ft. Where the freshwater lens is in contact with and extends downward into the low-hydraulic-conductivity volcanic rocks underlying the limestone (fig. 6), the freshwater in the limestone is commonly called "para-basal" water (Mink, 1974). The areas of para-basal water were recommended by Mink (1974) as prime targets for groundwater development because they were considered less vulnerable to saltwater intrusion from below. Recently, the term supra-basal water was proposed to describe water that is underlain by the low-hydraulic-conductivity rock above sea level (AECOM Technical Services Inc., 2011). These water bodies are isolated occurrences where water is in a basin of limestone completely surrounded by volcanic rock (fig. 6), and all evidence indicates that they are not hydrologically connected to the freshwater lens (other than water spilling over the edge of the basin to recharge the lens).

Following the recommendations of the Camp Dresser McKee report (1982), GEPA delineated the NGLA into six hydrologically connected aquifer basins for management purposes: the Agafo Gumas, Andersen, Finegayan, Hagåtña, Mangilao, and Yigo-Tumon basins (fig. 3). Vann and others (2013) proposed a redelineation of the basin boundaries on the basis of their updated basement topography map (fig. 4) and groundwater flow paths from the numerical model described in Rotzoll and others (2013). However, because these proposed boundaries have not currently (2013) been adopted for management use, the older boundaries have been retained for this report.

The freshwater lens in the study area forms because of the density difference between freshwater and underlying saltwater, 62.42 lb/ft^3 (1,000 kilograms per cubic meter [kg/m^3]) and 63.98 lb/ft^3 (1,024 kg/m^3), respectively. The lens thickness can be estimated by using the Ghyben-Herzberg relation (as described, for example, by Freeze and Cherry, 1979).

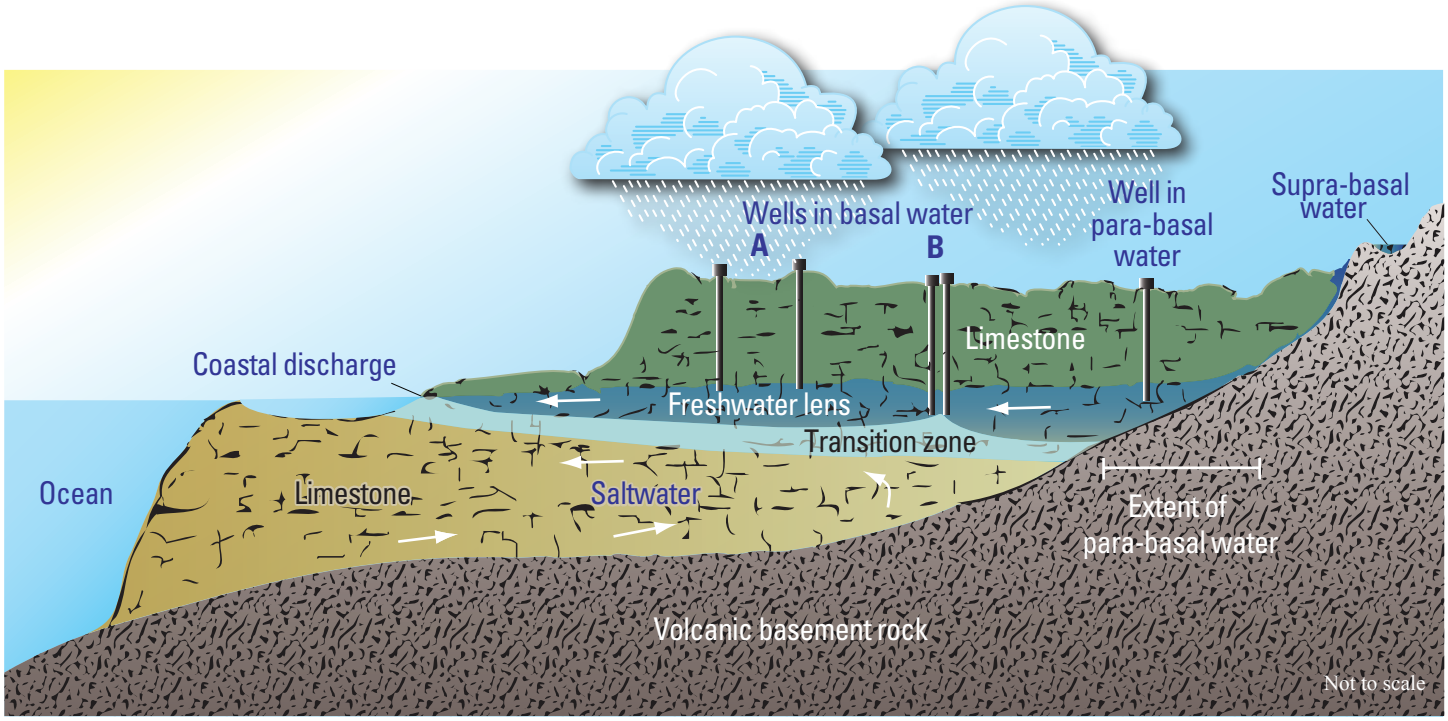


Figure 6. Schematic cross section of the study area showing groundwater occurrence and movement, Northern Guam Lens Aquifer, Guam.

Although the relation assumes that freshwater and saltwater do not flow or mix, it can be used where the flow is primarily horizontal to estimate the depth at which salinity is about 50 percent that of seawater. For these conditions, the freshwater-lens thickness below sea level is directly proportional to the height of the top of the freshwater above sea level. For example, where the water table is 1 ft above sea level, 40 ft of freshwater will be below sea level, so the freshwater lens will thus be 41 ft thick. This relation exists because the density ratio of saltwater to freshwater is 41:40. In the NGLA, freshwater mixing with underlying saltwater creates a brackish-water transition zone and the depth where the water has a salinity about half of that as seawater is assumed to be the midpoint of the transition zone. (To restate, for the purposes of this report, brackish water is considered water with salinity that ranges between greater than 2.6 percent seawater salinity [or greater than 500 mg/L chloride concentration] to less than 100 percent seawater salinity.)

Recharge

Freshwater-lens systems are recharged by rainfall infiltration. Early recharge estimates on Guam were directly linked with estimates of potential sustainable yield, the amount of water that could be "safely" exploited from the aquifer. Recharge estimates for the NGLA were made for varying areas of the aquifer (Mink, 1976; Camp, Dresser & McKee Inc., 1982; Mink, 1991; Jocson and others, 2002; Habana and others, 2009) to update sustainable-yield estimates. Sustainable-yield estimates for the NGLA evolved from 50 Mgal/d (Mink, 1976) to 57 Mgal/d (Camp, Dresser & McKee Inc., 1982) to 70–80 Mgal/d (Barrett Consulting Group, 1992) as more data became available. The first two estimates assigned sustainable yield as a fraction of recharge based on a steady-state approach and an average groundwater head. The third estimate used a transient approach to account for seasonal variation in recharge. Recharge for all three estimates was calculated from average monthly rainfall minus evapotranspiration; evapotranspiration values were estimates based on water balances used in Hawai‘i (Barrett Consulting Group, 1992). Recharge estimates from these water-budget investigations used monthly periods and could underestimate recharge. In contrast, water-budget models that use daily time steps provide a more accurate accounting of short-duration rainfall events and daily evapotranspiration (Oki, 2008). More recently, Jocson and others (2002) and Habana and others (2009) used water budgets that operated on daily time steps to estimate recharge for parts of northern Guam. Studies that are more recent have investigated the timing of individual rain events and the role of the unsaturated zone in recharge. From their numerical modeling study, Contractor and Jenson (2000) concluded that temporary storage of infiltrating water in the vadose zone is significant and infiltration rates are strongly dependent on the water content of the vadose zone at the time of the rain event. Jocson and others (2002) concluded that rapid infiltration after large rainfall events might not contribute to aquifer storage and that sustainable-yield estimates based on recharge would be too high, but they ultimately accepted the estimates of 70–80 Mgal/d as reasonable for the NGLA in the absence of a more detailed understanding of the processes that control aquifer recharge and storage. Comparison of groundwater and rainwater oxygen isotopic compositions indicates that (1) recharge happens by rapid infiltration with little evaporation before recharge and (2) recharge generally occurs above monthly rainfall thresholds of about 7.9 in. (Jones and Banner, 2003). Analysis of cave dripwater oxygen isotopes in northern Guam by Partin and others (2012) suggests that little or no recharge occurs at all during the dry season.

Most recently, Johnson (2012) estimated groundwater recharge for the entire island of Guam for the period 1961–2005 using a daily water-budget model that accounts for the spatial and temporal distributions of rainfall, irrigation, water-main leakage, septic-system leachate, evapotranspiration, runoff, soil type, and land cover. The water-budget model in this study differed from previous water-budget investigations on Guam by directly accounting for canopy evaporation in forested areas, quantifying the evapotranspiration rate of each land-cover type, and accounting for evaporation from impervious areas. For the parts of the aquifer defined by Mink (1991), which encompass most of the island's northern half, mean annual baseline recharge computed in the study is 238.0 Mgal/d (about 49 in/yr averaged over the area), which is 51 percent of mean annual rainfall (fig. 7). This estimate is slightly lower than Mink's (1991) estimate of 254 Mgal/d. For the drought estimation (Johnson, 2012), total recharge during drought conditions is 32 percent lower than mean baseline recharge. For the future land-cover water-budget simulation, which represents potential land-cover changes from the military relocation and population growth, estimated recharge for the entire island is nearly equal to the baseline recharge estimate that was based on 2004 land cover.

Discharge

Discharge from the study area is in the form of groundwater withdrawals from pumped wells, diffuse seepage to the ocean, and minor discharge to the Hagåtña Swamp. Withdrawals from pumped wells have been measured in most locations, although records are incomplete for some periods and locations. Diffuse seepage to the ocean was estimated at several locations.

Withdrawals From Wells

Significant withdrawals from the NGLA began during the wartime era of the 1930s and 1940s (H.T. Stearns, unpublished manuscript, 1937; Sundstrom, 1947). About 80 wells, including 2 Maui-type shafts excavated at the water table, were producing about 7 Mgal/d from the NGLA in 1947 (Sundstrom, 1947). Many of these wells were later abandoned. Ward and others (1965)

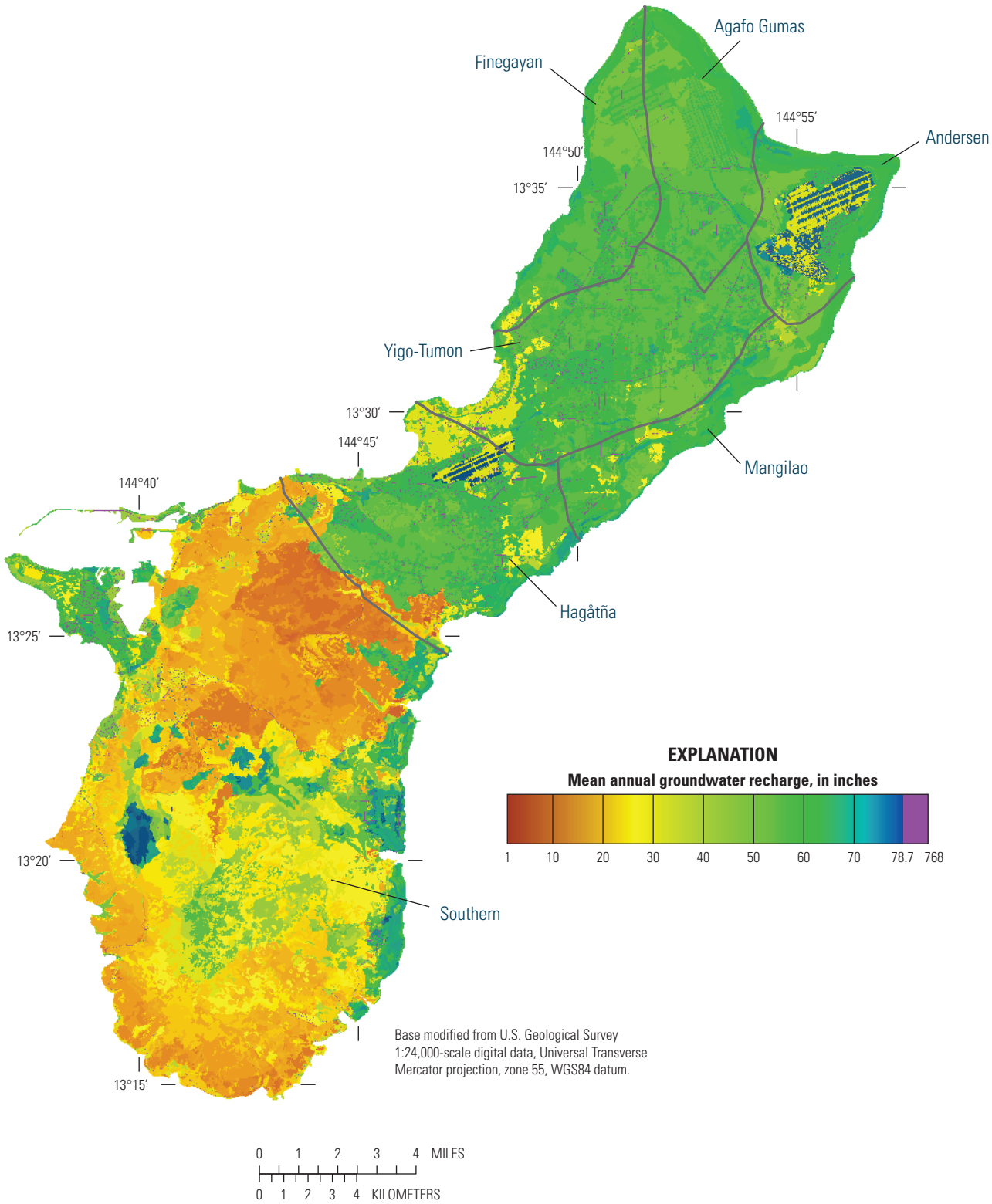


Figure 7. The distribution of mean annual groundwater recharge for baseline conditions on Guam calculated by using the water-budget model (Johnson, 2012). Enhanced recharge (colored purple) is where recharge is greater than 78.7 inches and is due to water input from water-main leakage, septic systems, or stormwater runoff. Boundaries of aquifer sectors are shown in gray.

reported about 213 wells withdrawing about 2–3 Mgal/d in 1963. In 1974, 77 wells were withdrawing about 23 Mgal/d of freshwater from the NGLA (Mink, 1974), and withdrawal in 1986 was reported at about the same rate (Guam Environmental Protection Agency, 1986). By 1996, withdrawals increased to about 35 Mgal/d (U.S. Department of Agriculture, 1999). Recent (2010–11) withdrawals were compiled from unpublished records provided by GWA, DoD, and GEPA in digital files and total about 42 Mgal/d from 153 wells.

Coastal Springs

Various investigators have described freshwater discharge at or near sea level around northern Guam (Emery, 1962; Matson, 1993; Jocson and others, 1999; Mylroie and others, 2001; Taboroši and others, 2009, 2013). Because of the difficulty in making accurate and inclusive discharge measurements near and below sea level, no overall estimates of groundwater discharge were previously published. Some studies focused on estimating discharge from individual features or groups of features that were obvious locations of significant groundwater discharge. For example, Jocson and others (1999) estimated discharge ranging from 5 to 9 Mgal/d per mile of coastline based on estimates at the most visible freshwater discharge features. Their measurements were along the deeply scalloped coastal embayments from Tumon to Haputo Bay (fig. 1). Later studies further identified and characterized features without estimating the volume of discharge at those features. Taboroši and others (2013) provide evidence of about 25 major discharge features along 6.5 miles (mi) of coastline from Tumon to Haputo Bay but only four features along the next 5.7 mi of coastline to the north. They suggest that the geographic pattern of discharge along certain sections of the coast is a reflection of the size and geometry of the basin in which the water originates. However, near Haputo Bay, the high aquifer hydraulic conductivity in this area (fig. 5) is probably an even more significant reason for the concentrated groundwater discharge.

Assuming that all groundwater that enters the freshwater lens as recharge eventually is withdrawn by wells or discharges at the coast allows a simple calculation to be made of coastal discharge. If average groundwater recharge to the NGLA is about 238 Mgal/d (Johnson, 2012) and withdrawal is currently about 42 Mgal/d then roughly 196 Mgal/d of freshwater is discharging as coastal seeps and springs.

Water Levels

Groundwater flow directions commonly are inferred from groundwater levels measured in wells. Groundwater levels also are an indicator of changes in recharge or withdrawals from the groundwater system and can be an indicator of freshwater-lens thickness. In the study area, groundwater levels vary spatially (horizontally and vertically) and temporally.

In general, measured water levels in the study area are lowest near the coast. Water levels increase inland toward the island's interior, farthest from the discharge areas at the coast (fig. 8). Because of the high aquifer hydraulic conductivity in the island's interior, horizontal water-table gradients in these rocks are small, about 0.25 foot per mile (ft/mi) (Rotzoll and others, 2013). In the relatively lower hydraulic conductivity rocks around the island's periphery, horizontal gradients are larger, about 2 ft/mi. In the Argillaceous Limestone of lower hydraulic conductivity in the southern part of the NGLA and in a small area of the Agafo Gumas basin, gradients are about 7 to 42 ft/mi. Water-level information is not available for determining vertical gradients, but heads in the aquifer near inland recharge areas likely may decrease slightly with depth as recharging water flows downward, whereas heads in the aquifer near coastal discharge areas likely may increase with depth as discharging water flows upward.

Water levels in northern Guam's wells rise and fall in response to short- and long-term changes in sea level and to changes in recharge and pumping (Ward and others, 1965, Ayers and Clayshulte, 1984; Gingerich, 2003; Rotzoll and others, 2013). In wells closest to the coast, water levels fluctuate daily as much as 0.5 ft in response to ocean tides. Wells in the high-hydraulic-conductivity limestone in the island's interior typically show much smaller daily fluctuations. Although data are sparse, wells in the low-hydraulic-conductivity volcanic rocks probably have minor or no daily water-level fluctuations from ocean tides but show more response to local recharge. Water-level fluctuations caused by changes in recharge depend on the rainfall amount and location and the aquifer hydraulic properties in the area near the well (Lander and others, 2001). In addition to the daily fluctuation in water level caused by the daily ocean tides, water levels in high-hydraulic-conductivity rocks also vary over longer times in response to nonperiodic changes in sea level (Gingerich, 2003). Water-level records with the tidal fluctuations removed show variations over several-month time scales that correspond closely to the sea-level record. Because of the very high aquifer hydraulic conductivity, pumping effects from nearby wells are generally too small to discern in water-level records.

Continuous water-level measurements in observation wells, some since the 1970s, are available from the USGS National Water Information System (NWISWeb). For this study, the long-term monitoring network was augmented by collecting continuous water-level measurements in 20 wells concurrently during 2010 (table 1; fig. 8). Measuring points for each of the wells were resurveyed so all wells were tied into a common, updated sea-level datum (GUVD04). All but one of the measured water-level values were determined by averaging water levels recorded electronically at 15-minute intervals during various periods of 2010. Because water levels in the freshwater lens are influenced by the sea-level height, each average water-level value was normalized by subtracting the average sea level during each well's monitoring period to obtain water levels based on the same reference sea level (table 1). Monthly sea-level data for the Apra Harbor Tide gage were downloaded from National Oceanic and Atmospheric Administration (2012). Because ACEORP Tunnel

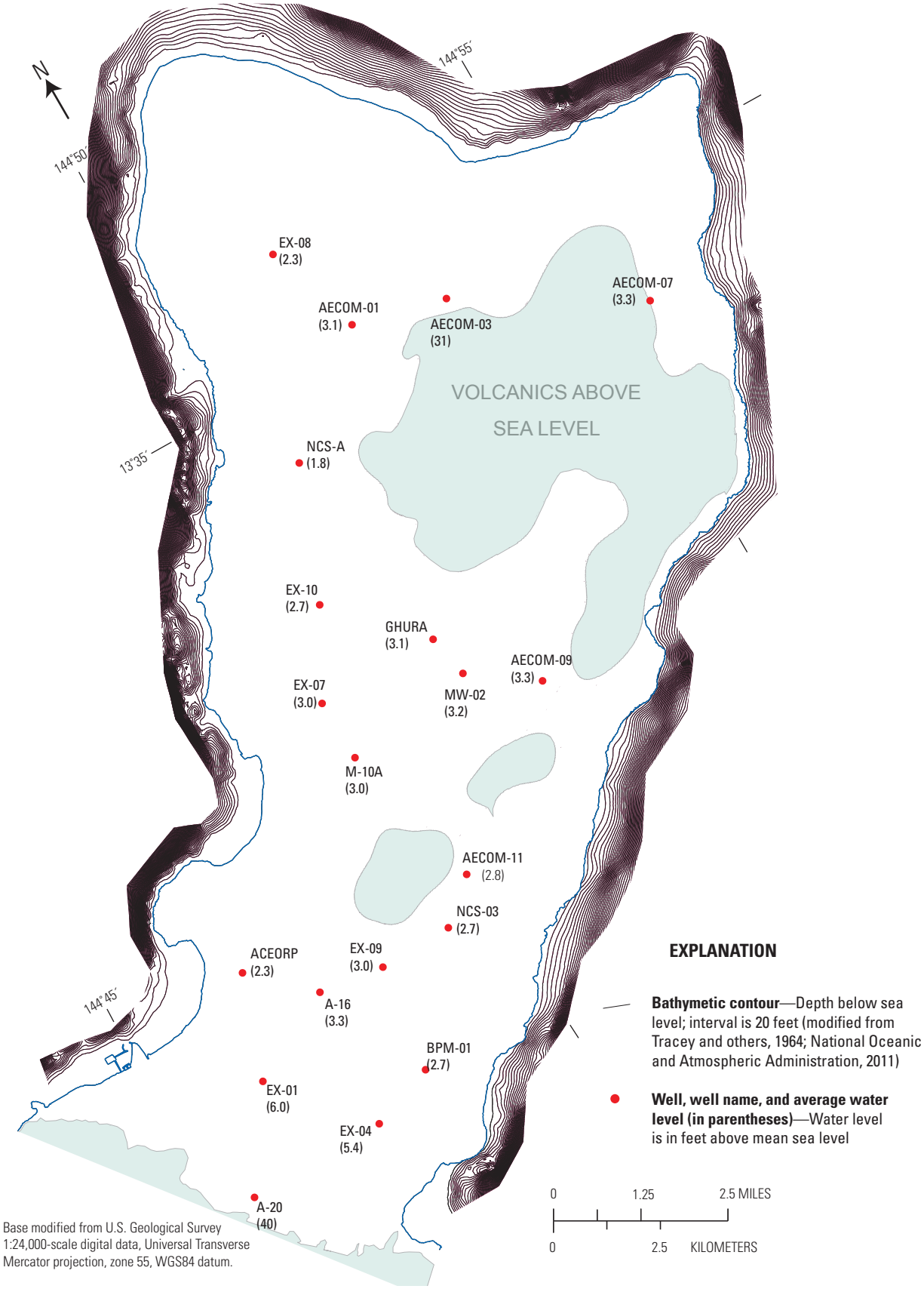


Figure 8. Measured water levels during 2010 in selected wells in the Northern Guam Lens Aquifer, Guam.

(fig. 8) was not monitored during 2010, 2008 water-level and sea-level data were used to determine an adjusted average water level for this well (ACEORP Tunnel is a 700-ft-long horizontal shaft well excavated at the water table). Rainfall and withdrawal conditions during 2008 and 2010 were judged similar enough that no further adjustment was needed for the ACEORP Tunnel water-level estimate.

Unadjusted average water levels during 2010 ranged between 2.27 and 39.69 ft above mean sea level (table 1). During the measuring period, the average sea level was above mean sea level and the adjustments to each well's measured water level ranged between 0.30 and 0.53 ft downward. Wells AECOM-3 and A-20 were not adjusted because water levels in these lower hydraulic conductivity parts of the aquifer were assumed unaffected by sea-level fluctuations. The ACEORP Tunnel adjustment was lower because it was based on a different period. After adjustment, average water levels ranged from 1.78 ft near the coast to nearly 40 ft in the low-hydraulic-conductivity Argillaceous Limestone (table 1).

Water-level changes over time can be compared between recent measurements and available measurements from 1986. Average water levels at eight wells where data are available are 0.03–4.65 ft lower in 2010 as compared to 1986 (table 1), with the median decrease in water level being about 0.26 ft. Water-level data during 1986 were corrected for monthly sea-level variation and to account for changes in measuring-point elevation at each of the wells based on a 2004 resurvey effort. The correction to each water level to account for the update in the measuring point was made with the assumption that the resurveyed measuring-point elevation was applicable to the 1986 measurements. This assumption may introduce some error, because the source of the benchmark data used for water levels prior to the 2004 resurvey is unknown. Benchmark elevations in 2004 averaged -0.1 ft lower compared to the 1963 elevations; however, the distribution of changes varies widely and appears to follow no pattern, and the discrepancy is considered unexplainable (Carlson and others, 2009). The decrease in water levels between 1986 and 2010 could be attributed to increased groundwater withdrawal (23 Mgal/d in 1986 compared to 42 Mgal/d in 2010) or decreased recharge. Recharge calculations specifically for these two years are not available; however, rainfall at the Guam International Airport

Table 1. Measured and simulated water levels in selected wells, Northern Guam Lens Aquifer, Guam.

[–, not applicable; -, no adjustment made; online data available from *http://waterdata.usgs.gov/gu/nwis/si*]

Well name	Measured average water level during 1986 (feet)	Adjustment for measuring-point update and measured average sea level during period well was monitored (feet)	Adjusted average water level during 1986 (feet)	Measured average water level during 2010 (feet)	Measured average sea level during period well was monitored (feet)	Adjusted average water level during 2010 (feet)	Simulated water level (feet)
NCS-A	–	–	–	2.27	0.48	1.78	2.20
ACEORP	2.42	–0.20	2.62	2.99[a]	0.69	2.30	2.64
EX-8	–	–	–	2.83	0.49	2.34	2.64
NCS-3	–	–	–	3.14	0.47	2.67	2.71
AECOM-11	–	–	–	3.17	0.49	2.67	2.65
BPM-1	2.69	–0.01	2.70	2.97	0.30	2.67	2.83
EX-10	2.75	–0.22	2.97	3.03	0.31	2.73	2.67
EX-7	3.22	–0.14	3.36	3.30	0.36	2.94	2.83
EX-9	2.91	–0.14	3.05	3.43	0.48	2.95	2.93
M10-A	2.71	–0.57	3.28	3.37	0.36	3.01	2.92
GHURA-Dededo	–	–	–	3.52	0.48	3.04	3.01
AECOM-1	–	–	–	3.54	0.49	3.04	2.60
MW-2	–	–	–	3.66	0.47	3.19	3.11
A-16	3.62	0.08	3.54	3.65	0.36	3.29	3.13
AECOM-7	–	–	–	3.81	0.47	3.34	3.24
AECOM-9	–	–	–	3.88	0.53	3.35	3.23
EX-4	–	–	–	5.91	0.50	5.41	5.46
EX-1	–	–	–	6.50	0.48	6.02	6.04
AECOM-3	–	–	–	31.21	-	31.21	30.71
A-20	44.37	0.03	44.34	39.69	-	39.69	38.48

[a]Measured during 2008.

was about 100 in. during 1985 and 2009 (National Climatic Data Center, 2010), indicating that recharge was probably similar before both periods. Therefore, the decrease in water levels appears attributable mainly to increased withdrawal from the NGLA.

Salinity

Salinity is one of the main factors controlling groundwater availability in the NGLA. For the purposes of this report, salinity is usually expressed as chloride concentration. In general, the salinity of water withdrawn from wells in the area increases with depth, proximity to the coast, and withdrawal rate, although exceptions to this generalization occur. In 2000–10, public supply wells in the NGLA produced water with chloride concentrations ranging from less than 30 mg/L to greater than 500 mg/L (Simard, 2012; Simard and others, 2013) (fig. 9). These values are equal to about 0.2 percent to 2.6 percent seawater salinity, assuming seawater has a chloride concentration of 19,600 mg/L. The wells producing the least saline water are generally farther inland and completed at the shallowest depths in the freshwater lens. The wells producing the most saline water are generally closer to the coast, completed deeper in the freshwater lens, or pumped at the highest rates (McDonald and Jenson, 2003; Simard, 2012; Simard and others, 2013). The two areas having wells producing the highest salinity water are the eastern part of the Hagåtña basin and the Finegayan basin.

Linear regression analysis of chloride concentrations generally revealed statistically significant upward trends in chloride concentration in 118 of the 153 production wells in the NGLA between 1973 and 2010 (Simard, 2012; Simard and others, 2013). Additionally, the chloride trends showed increased variability during the 1990s and 2000s when compared to earlier years. Wells in basal and para-basal areas had cyclical chloride trends with varying periodicity. The cyclical patterns are most likely correlated with the fluctuations due to El Niño/La Niña episodes superimposed on a trend of rising sea level (Simard, 2012).

Periodic specific-conductance and chloride-concentration measurements (indicators of salinity) in deep wells that penetrate into or through the freshwater/saltwater transition zone provide information about the thickness and seasonal variation of the freshwater lens. Water samples from various depths in the deep wells were collected starting in the early 1980s and were analyzed for specific conductance and chloride concentration. Since 2000, salinity profiles have been collected by using a conductivity/temperature/pressure sensor lowered into the deep wells. For this study, seawater was assumed to have a specific conductance of 51,300 µS/cm, the maximum value measured. Measured specific conductance was divided by 51,300 µS/cm and multiplied by 100 to obtain salinity in terms of percent of seawater salinity.

The freshwater thickness (less than 500 mg/L chloride concentration or about 2.6 percent seawater salinity) is greatest in the Hagåtña basin at wells EX-1 and EX-4, ranging from about 120 to 140 ft. The transition-zone thickness also is the greatest at EX-1, about 300 ft (fig. 10). The thick transition zone is related to the relatively low hydraulic conductivity of the Argillaceous Limestone in this area. The freshwater lens farther to the north is thinner, about 90–110 ft thick, at the rest of the deep monitoring wells. However, the transition-zone thickness at these wells is significantly less, ranging from 35 ft at well GHURA-Dededo to 115 ft at well EX-9 (fig. 10).

Analysis of five years of salinity-profile data from these wells revealed several important findings (Simard, 2012; Simard and others, 2013):

1. The thickness of the zone of freshest water (defined in their study as less than 250 mg/L chloride concentration or about 1.3-percent seawater salinity [the Guam Environmental Protection Agency (2001) secondary standard for chloride concentration]) varies seasonally due to recharge by as much as 230 ft in the Argillaceous Limestone.

2. The thickness of the zone of freshest water varies seasonally by only about 15 ft further north in the Barrigada Limestone.

3. The depth of the transition-zone midpoint (9,800 mg/L chloride concentration or 50-percent seawater salinity) decreased during 2005–09 by about 16 to 43 ft in the Argillaceous Limestone and 3 to 20 ft in the Barrigada Limestone.

Comparison of the recent data with older measurements shows that the depth of the transition-zone midpoint moved upward at well EX-7, ranging from about -129 to -145 ft altitude during 1984–88 (Gingerich, 2003) and from about -114 to -127 ft altitude during 2005–09 (Simard, 2012). Significant upward movement of the transition zone is also apparent at well EX-1 (-236 to -292 ft during 1984–88 and -200 to -257 ft during 2005–09). However, no upward movement is apparent at well EX-9 (-116 to -122 ft during 1984–88 and -113 to -131 ft during 2005–09).

Simard (2012) estimated the ratio of the depth to the transition-zone midpoint to the hydraulic head at the water table to be 36:1 on basis of the existing salinity profiles from the NGLA. The decrease in head at well EX-7 during 1986–2010 was about 0.42 ft (table 1). Applying the 36:1 ratio to this head change results in a related decrease in the depth of the transition-zone midpoint by 15 ft, an estimate that compares well with the measured change during the mid-1980s through 2009. Applying the same analysis to the head change observed at well EX-9 indicates a decrease in the transition-zone midpoint of only about 4 ft, again comparing well with the measured changes.

Salinity profiles from deep open boreholes may be affected by flow within the borehole (Paillet and others, 2002; Rotzoll, 2010). Borehole flow can be caused by natural and withdrawal-induced vertical-head differences in the aquifer. Head may increase with depth in the aquifer near coastal

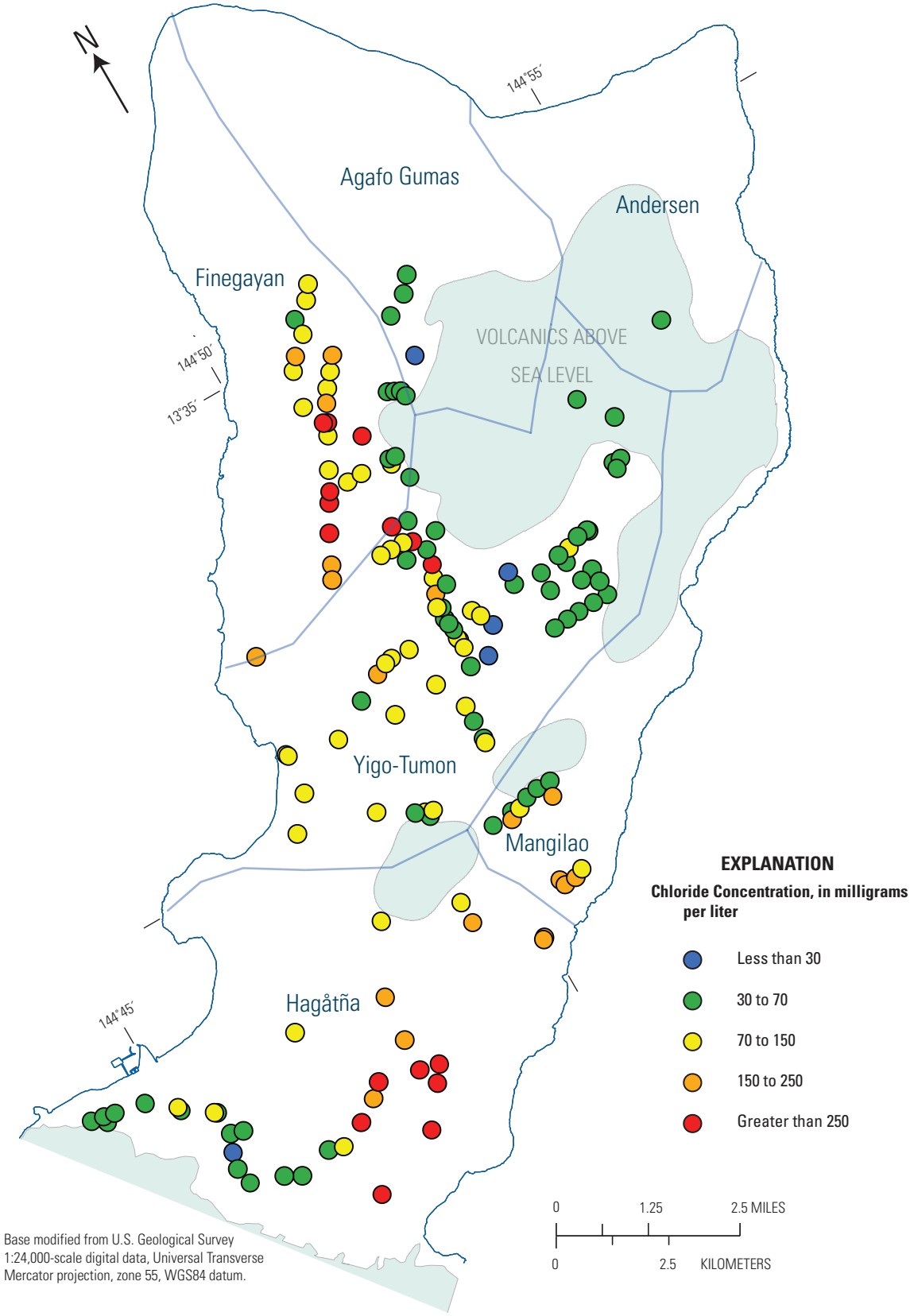


Figure 9. Average chloride concentration during 2000–10 in wells in the Northern Guam Lens Aquifer, Guam (modified from Simard, 2012).

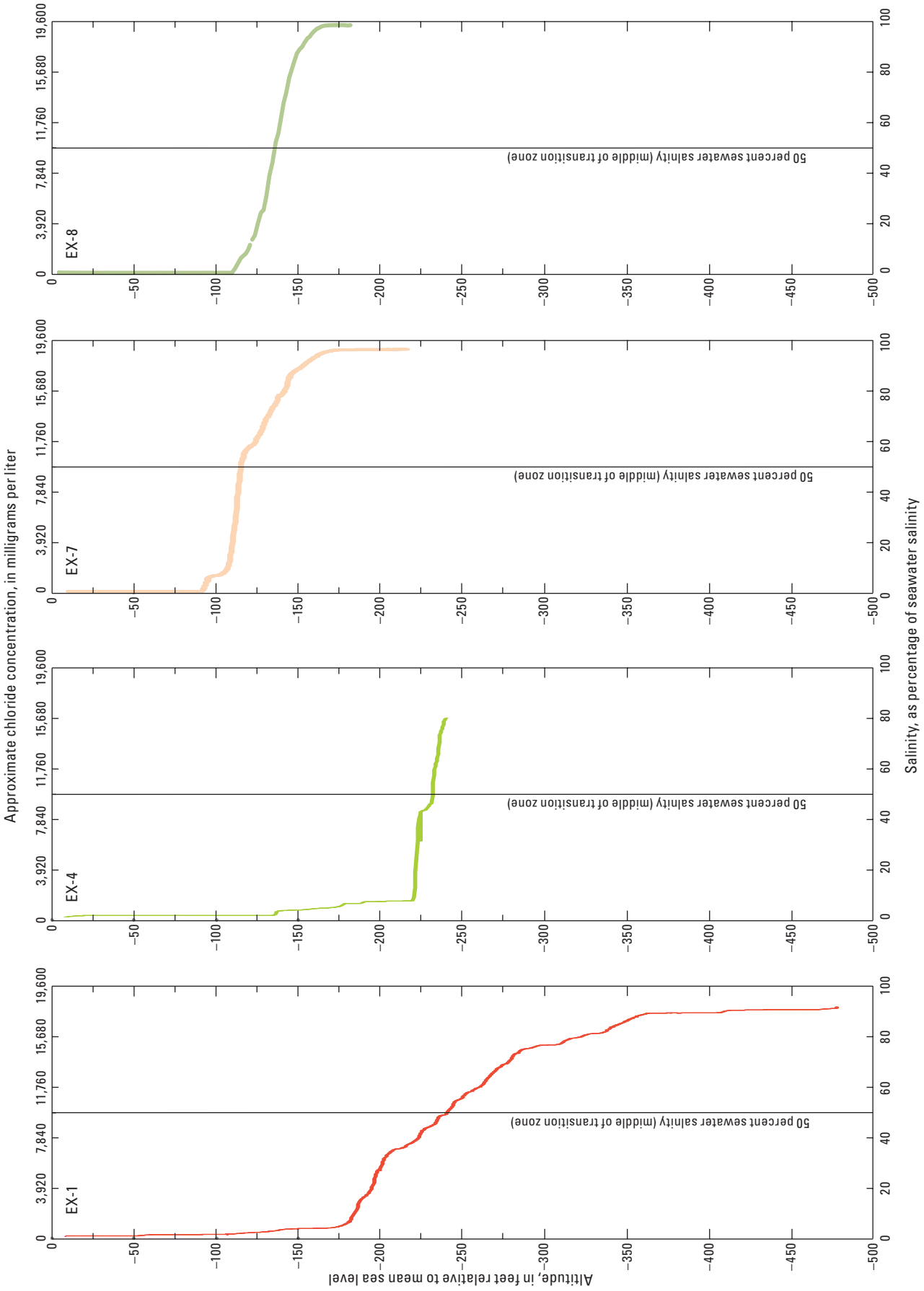


Figure 10. Measured salinity profiles in selected monitoring wells (December 2009 or May 2010 [EX-8]), Northern Guam Lens Aquifer, Guam.

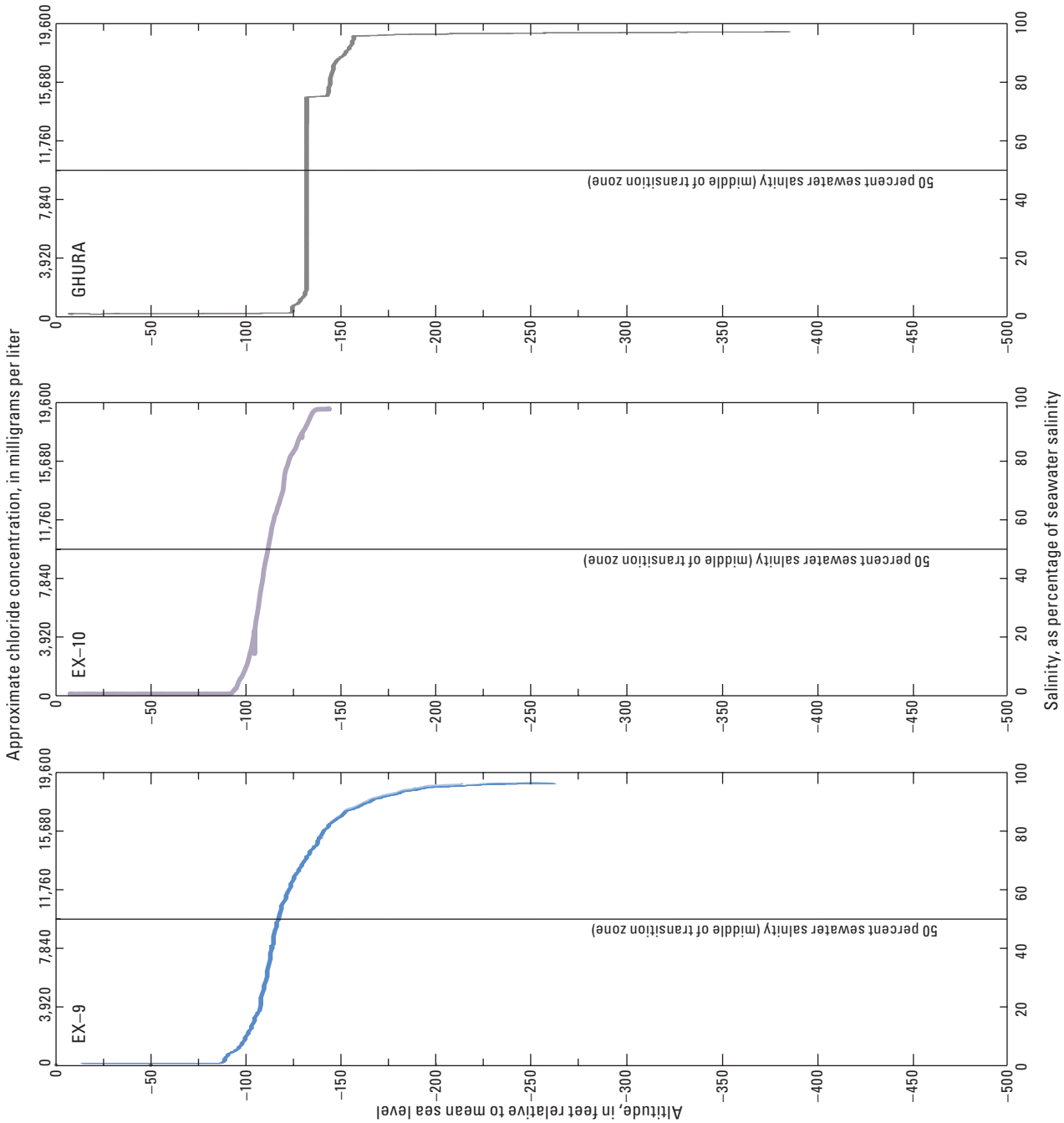


Figure 10. Measured salinity profiles in selected monitoring wells (December 2009 or May 2010 [EX-8]), Northern Guam Lens Aquifer, Guam.—Continued

discharge areas and near partially penetrating pumped wells, and increasing head in the aquifer with depth may lead to upward flow within an open borehole. Upward borehole flow may cause saltwater to flow upward in the borehole, which in turn may lead to an underestimate of the freshwater-lens thickness based on the recorded salinity profile. In areas where head decreases with depth, downward borehole flow may exist and lead to an overestimate of the freshwater-lens thickness based on the recorded salinity profile. Currently, no published studies of borehole flow on Guam are available to indicate whether borehole flow is significantly altering the observed salinity profiles.

Simulation of Groundwater Flow

The numerical model developed for this study is a three-dimensional model that simulates the transition from freshwater to saltwater. The model code used for this study was SUTRA (version 2.2) (Voss and Provost, 2002, version of September 22, 2010), a finite-element code that simulates fluid movement and the transport of dissolved substances in groundwater. SUTRA is capable of simulating three-dimensional, variable-density groundwater flow and solute transport in heterogeneous anisotropic aquifers. Model construction was facilitated by use of a graphical user interface (SutraGUI) (Winston and Voss, 2003) capable of reading geographic information system (GIS) spatial data and creating files used by SUTRA. A steady-state model was developed for 2010 stress conditions and transient flow and transport were simulated for future withdrawal scenarios.

Model Construction

The numerical model of groundwater flow and transport was developed to simulate groundwater levels and changes in the extent of the freshwater lens in response to pumping. Model construction includes designation of spatial discretization, assignment of boundary conditions (including spatially varying recharge and withdrawals, and measured sea level) and initial conditions, and delineation of fluid and aquifer properties, including those of the unsaturated zone above the water table.

Model Mesh

The model finite-element mesh used for this study comprises 642,757 nodes and 609,280 elements, covers the entire freshwater-lens system in the NGLA, and extends as much as 1 mi offshore to include the zone where fresh groundwater discharges to the ocean (fig. 11). The entire mesh covers about 108 mi^2; the individual mesh elements range from 948 ft^2 to 2×10^6 ft^2 or roughly ranging from 30- by 30-ft elements to a 1,400- by 1,400-ft element. The model mesh excludes the19-mi^2 part of the island interior where the volcanics are above sea level, although recharge from these excluded areas is included in the model. The extent of the areas where volcanics are above sea level was extended to connect the discontinuous ridge formed along the southeast boundary of the Yigo-Tumon trough to account for the finding from the tidal analysis (Rotzoll and others, 2013) that the ridge is an effective hydrologic barrier (fig. 4).

The top of the onshore model domain ranges from 6 to 40 ft above sea level to allow the model to simulate the water-table surface. The top of the offshore model domain is the ocean bottom based on bathymetry (fig. 8) (Tracey and others, 1964; National Oceanic and Atmospheric Administration, 2011). The modeled domain extends from the unsaturated zone above the water-table surface to the base of the limestone aquifer and ranges from 10 ft in thickness where the volcanics rise above sea level to more than 1,500 ft in thickness near Guam's northeast tip. Node spacing is variable in the vertical and horizontal directions and is finest in the upper part of the aquifer and near areas of increased groundwater withdrawal and discharge. The limestone thickness is represented by 40 nodes; the spacing between each node grows by a factor of 1.05. Onshore, the vertical spacing between nodes varies from 0.03 ft within the top 10 ft of the aquifer to accurately represent the transition zone from freshwater to saltwater to 66 ft near the bottom of the modeled domain. Horizontal spacing is variable, ranging from 30 to 1,400 ft, but identical at all depths in the aquifer.

The unsaturated-flow option (Voss and Provost, 2002) used simple linear functions to determine relative permeability and saturation with pressure above the water table, as described in Voss (1999). For saturation, the function is linear between a saturation of 1 at a pressure of zero down to a residual saturation of 0.01 at a pressure of -408.2 lb/ft^2. For relative permeability, the function is linear between a relative permeability of 1 at a saturation of 1 down to a relative permeability of zero at a residual saturation of 0.01.

Boundary Conditions

The model domain is defined by boundaries that are either specified-pressure, no-flow, or recharge boundaries.

Specified-Pressure and No-Flow Boundaries

The top and vertical boundaries of the offshore part of the model domain are a specified-pressure (hydrostatic seawater) boundary condition. Pressure at each node along the offshore boundary is equal to the pressure exerted by the depth of seawater extending from the node to sea level. For all simulations, pressures were held constant in time. Flow across the offshore vertical boundary could either enter the model with salinity equal to that of seawater or exit the model with salinity equal to that of water in the adjacent node.

The southern and interior boundaries are formed by contact between the limestone and volcanics and are treated as no-flow boundaries in the model. The model bottom is assumed to be a no-flow boundary.

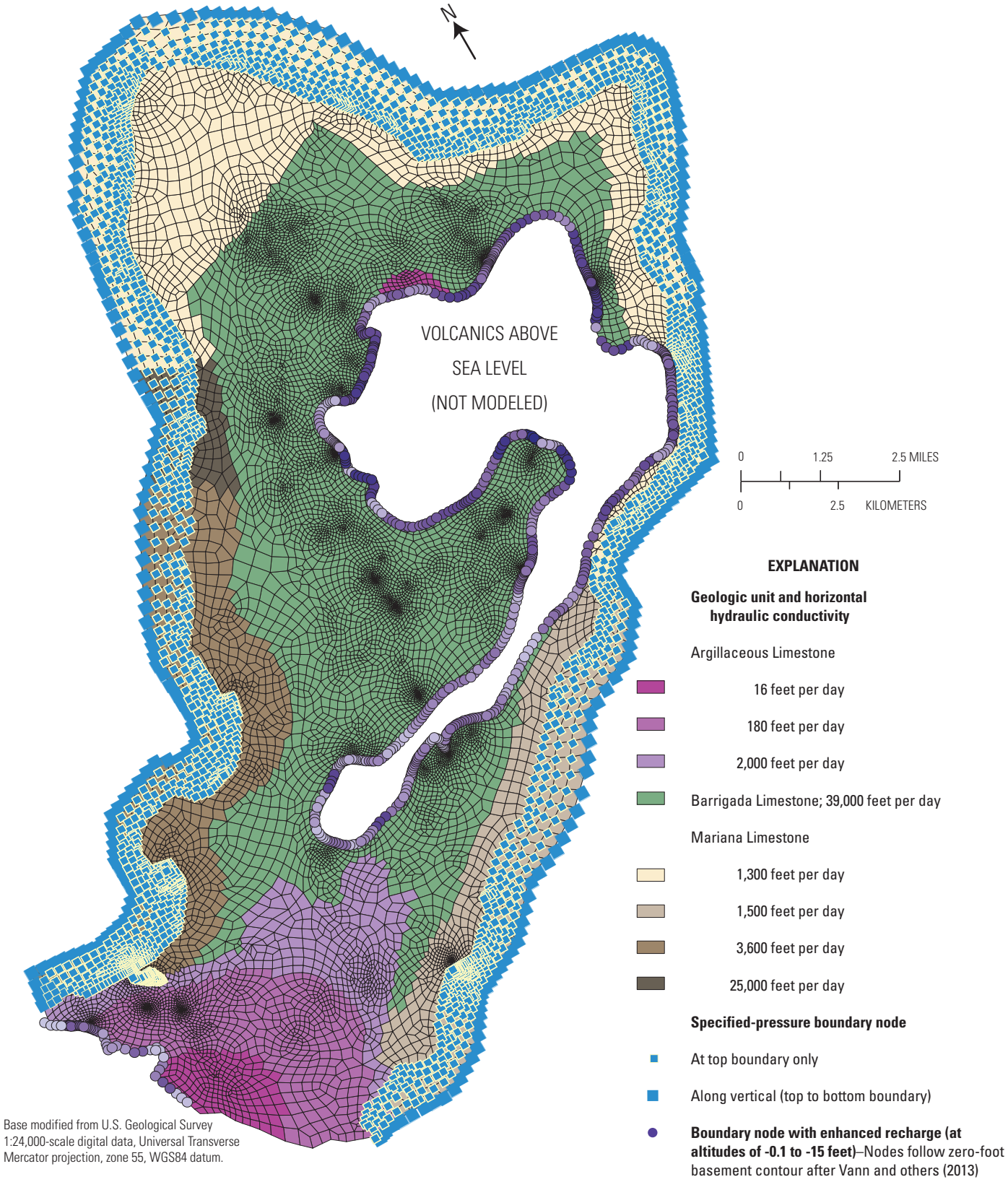


Figure 11. Model discretization and features for the numerical groundwater model mesh of the Northern Guam Lens Aquifer, Guam.

Recharge

Recharge to the model domain was based on the distributions estimated by Johnson (fig. 7, 2012). Recharge enters the model at the top boundary in onshore areas. Because the modeled area did not include the island interior where volcanics are above sea level, recharge from this area was distributed around the perimeter of the area assuming it percolates downslope on the volcanic surface until it reaches the limestone aquifer. Recharge from the interior boundary enters the model between altitudes of -0.1 ft and -15 ft relative to mean sea level. This interval was chosen because it is below the top layer of nodes, avoiding assigning two sets of recharge (lateral and areal) at the same node in SUTRA. All recharge was assumed to have a chloride concentration of about 30 mg/L (expressed as a mass fraction of 0.00006069 kg/kg in SUTRA), the average concentration measured in groundwater samples considered most representative of recharge (Johnson, 2012).

Withdrawal

Reported average withdrawals from wells during selected periods were simulated in the numerical model. Reported withdrawals were compiled from GWA, DoD, and GEPA digital records. Withdrawal wells (fig. 12) were represented in the model by the nearest vertical column of nodes to the withdrawal well. Only those nodes corresponding to the well interval open to the aquifer were used to simulate withdrawal. Withdrawal from the aquifer was assumed uniform within the well interval open to the aquifer (appendix 1). Withdrawal from the Tumon well, a shaft with a large-capacity 1,000-ft infiltration tunnel, was represented in the model by several nodes assuming a tunnel orientation perpendicular to the shoreline. In several cases where wells are closely spaced, a model node represented the sum of withdrawal from more than one well.

Water Properties

Water was assigned a fluid compressibility of 2.14×10^{-8} foot squared per pound (4.47×10^{-10} pascal^{-1}) and a dynamic viscosity of 2.1×10^{-5} slug per foot per second (1.00×10^{-3} kilogram per meter per second) and both were assumed to remain constant throughout time. Solute concentrations in SUTRA are expressed as a mass fraction: mass of total dissolved solids (TDS) per unit mass of fluid. Freshest water was assigned a TDS concentration of zero, and 100 percent seawater was assigned a TDS concentration of 3.57×10^{-2} kilogram per kilogram (35.7 ppt), but all values were converted to an equivalent value of seawater salinity or chloride concentration for easier discussion in this report. The water density was assumed to increase linearly with salinity from 62.42 lb ft^{-3} (1,000 kg m^{-3}) for freshwater to 63.98 lb ft^{-3} (1,024.99 kg m^{-3}) for ocean water.

Aquifer Properties

For the numerical model, aquifer properties were initially assigned values on the basis of previously published estimates (Rotzoll and others, 2013). The hydraulic-conductivity, dispersivity, and effective-porosity values for the different geologic areas were adjusted in the numerical model to provide a better match to measured water levels and salinity profiles from selected wells in the study area. Horizontal hydraulic-conductivity values used in the model ranged between 16 and 2,000 ft/d for the Argillaceous Limestone, 1,300 and 25,000 for the lower-conductivity limestone surrounding the plateau, and about 39,000 ft/d for the Barrigada Limestone (fig. 11, table 2). The range in hydraulic conductivity for the Argillaceous Limestone represents a gradational increase in hydraulic conductivity with distance from the volcanic uplands (presumably the source of clayey sediments in this formation) toward the island interior. Vertical hydraulic conductivity of the limestone aquifer in the model was about 5 times lower than the horizontal hydraulic conductivity for all units except the Barrigada Limestone. Owing to the extremely high horizontal hydraulic conductivity of the Barrigada Limestone, the vertical hydraulic conductivity was specified as 200 times lower to prevent numerical instability in the model.

For horizontal flow, the longitudinal dispersivity (parallel to flow) ranged from 200 to 250 ft, and the transverse dispersivity (perpendicular to flow) was assumed isotropic and ranged from 0.07 to 0.3 ft (table 2). For vertical flow, the longitudinal dispersivity ranged from 10 to 23 ft. Dispersivity values for flow directions other than horizontal or vertical were interpolated from these specified values, as described by Voss and Provost (2002). Molecular diffusivity was assigned a value of $1.1\text{x}10^{-8}$ ft^2/s ($1.0\ \text{x}10^{-9}$ m^2/s) in the model.

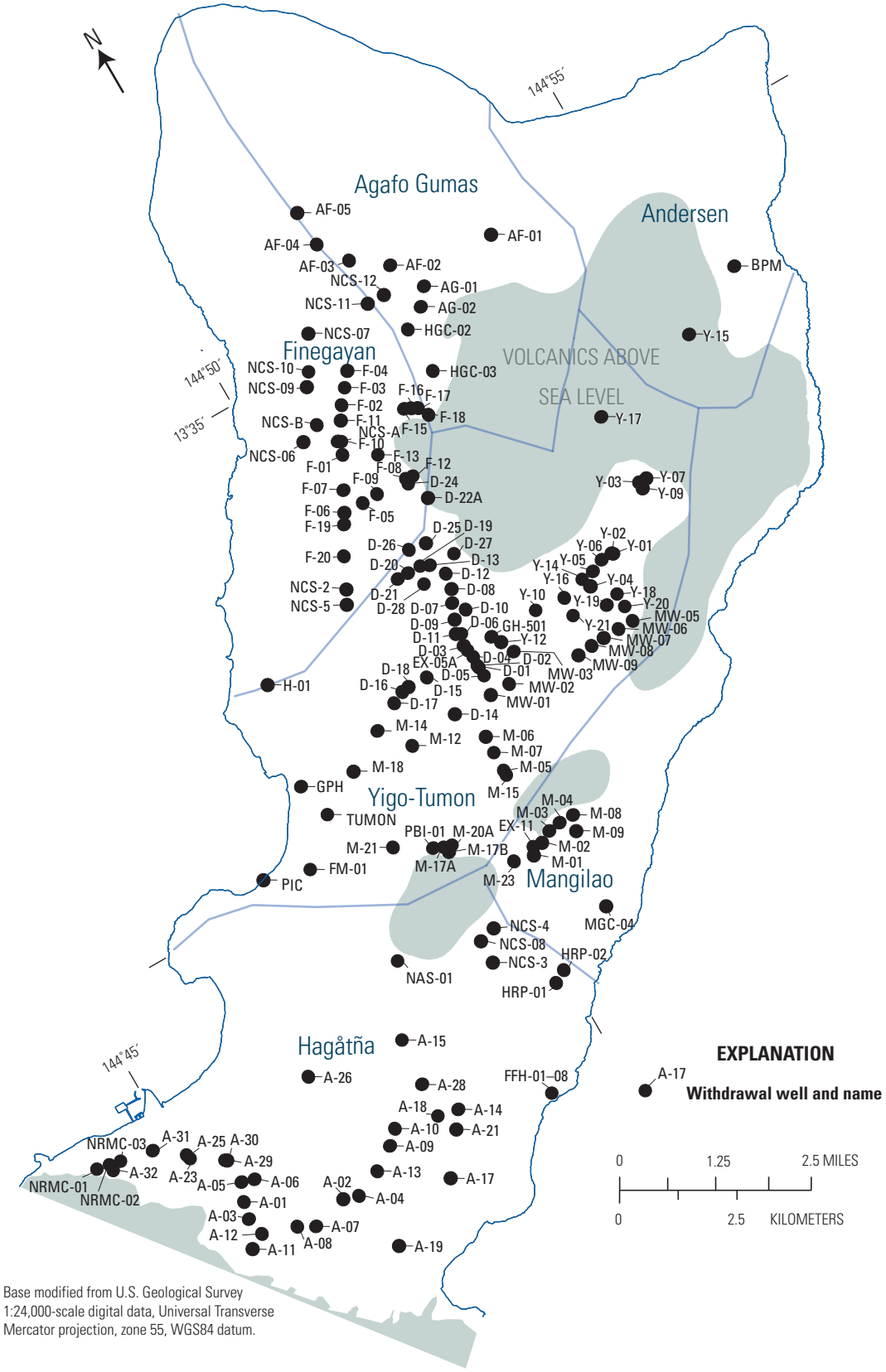


Figure 12. Selected withdrawal wells used in construction of the numerical groundwater model of the Northern Guam Lens Aquifer, Guam.

Table 2. Aquifer-property values used in the construction of the numerical groundwater model of the Northern Guam Lens Aquifer, Guam.

[ft, feet; ft/d, feet per day; ft^2/lb, feet squared per pound; values for transverse dispersivity are equal in x, y, and z directions]

Parameter	Estimated value		
Hydraulic conductivity (ft/d)	**Vertical**	**Horizontal, transverse**	**Horizontal, longitudinal**
Argillaceous Limestone			
zone A	3	16	16
zone B	35	180	180
zone C	400	2,000	2,000
Barrigada Limestone	200	39,000	39,000
Mariana Limestone			
zone D	250	1,300	1,300
zone E	310	1,500	1,500
zone F	710	3,600	3,600
zone G	5,000	25,000	25,000
Dispersivity (ft)	**Transverse**	**Longitudinal, minimum**	**Longitudinal, middle and maximum**
Argillaceous Limestone			
zone A	0.3	20	250
zone B	0.3	20	250
zone C	0.07	10	200
Barrigada Limestone	0.07	10	200
Mariana Limestone			
zone D	0.07	10	200
zone E	0.07	10	200
zone F	0.07	10	200
zone G	0.3	23	250
Effective porosity (and specific yield)			
Argillaceous Limestone			
zone A	0.005		
zone B	0.005		
zone C	0.05		
Barrigada Limestone	0.02		
Mariana Limestone			
zone D	0.3		
zone E	0.02		
zone F	0.4		
zone G	0.4		
Solid-matrix compressibility (ft^2/lb)	1.2×10^{-7}		

Table 3. Recharge for selected simulations, Northern Guam Lens Aquifer, Guam.

[All values in million gallons per day; estimated recharge modified from Johnson (2012); total recharge used in simulation is the sum of the estimated recharge to the modeled area and the estimated lateral inflow from the interior recharge area]

Model period	Estimated recharge		Total recharge used in SUTRA simulation
	Modeled area	Flow from interior recharge area	
2010, predevelopment, and future scenarios	184	41	225
1969–73 drought scenarios	127	28	155

Simulated Average Conditions

Average 2010 conditions were simulated by using 0.1-day time steps. Recharge rates (table 3) and withdrawal rates (table 4) were steady, and specified pressures representing the column of seawater were assigned a hydrostatic pressure equal to mean sea level. Where applicable, certain hydraulic properties used in the model were adjusted to obtain agreement between simulated and measured water levels and salinity profiles.

The final distribution of hydrologic parameters was determined through an extensive trial and error process to determine the most likely values. The trial and error fitting process included matching the tidal signal in 15 wells, matching average water levels at 19 wells, matching salinity profiles at 6 wells, and matching salinities at 138 pumped wells. Aquifer properties (hydraulic conductivity, effective porosity, dispersivity) were adjusted in a wide range of reasonable values, and a suitable combination of values was found that produced a reasonable match between simulated heads, gradients, and salinities to the historic hydrologic data.

Water Levels

Simulated water levels generally are in agreement with measured water levels from available wells in the modeled area (table 1 and fig. 13). Throughout the NGLA, simulated water levels generally match the average water-level distribution (fig. 14). The best match to measured water levels was obtained in the central and southern part of the study area where the knowledge of the aquifer is greatest. The areas where the match is not as good are in the north near wells NCS-A, AECOM-01, and EX-08. The high-hydraulic-conductivity zone near NCS-A is needed to allow water levels to remain lower around NCS-A. The groundwater mound to the northwest of EX-08 has not been confirmed with recent data. The high water levels near AECOM-03 were achieved by using an area of low hydraulic conductivity representing argillaceous limestone; however, limited hydrologic data are available in this area to confirm this representation.

Some of the discrepancy between measured and simulated water levels can be attributed to uncertainties in the estimated distribution of hydraulic properties in the numerical model or model spatial discretization that may be too coarse in some areas to accurately simulate local water levels.

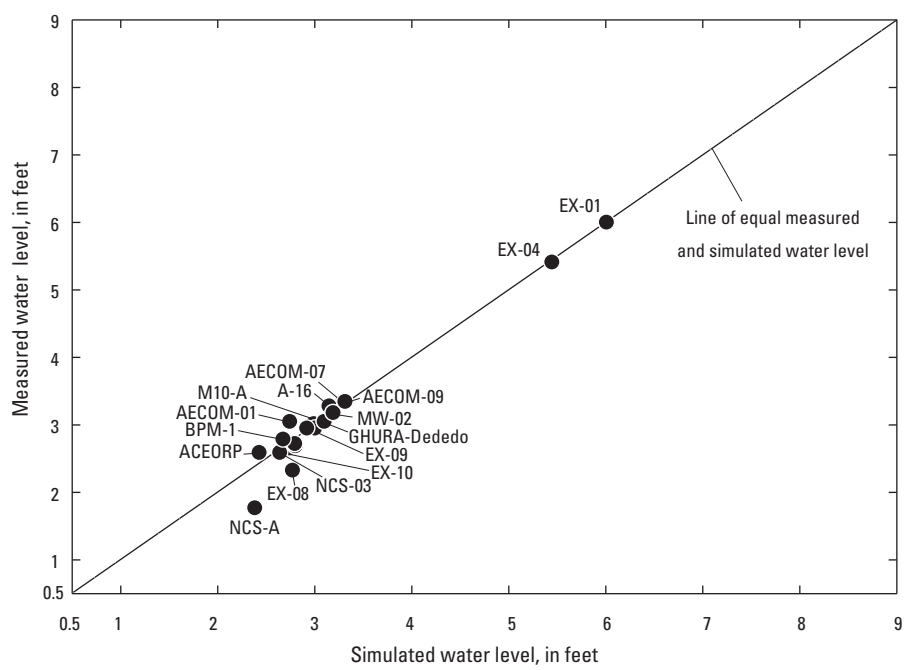


Figure 13. Graph comparing measured and simulated water levels in selected wells in the Northern Guam Lens Aquifer, Guam.

Table 4. Selected wells and withdrawal rates used in calibration and drought scenarios, Northern Guam Lens Aquifer, Guam.

[Values in pink or red represent wells with salinity in the cautionary or threatened range, respectively; cautionary yield is the volume of withdrawn water that has a salinity roughly from 200 to 500 milligrams per liter of chloride; threatened yield is the volume of withdrawn water that has a salinity greater than roughly 500 milligrams per liter of chloride; well information and withdrawal rates provided by Guam Water Authority (GWA), Department of Defense (DoD), and Guam Environmental Protection Agency; modeled salinity is the average salinity from all of the nodes representing each pumped well]

Well name	Well owner	Withdrawal rate (million gallons per day)		
		Average 2010	Drought	Drought-reduced withdrawal
		Agafo Gumas basin		
AF-01	DoD	0.2485	0.2485	0.2485
AF-02	DoD	0.1817	0.1817	0.1817
AF-03	DoD	0.2098	0.2098	0.2098
AF-04	DoD	0.1944	0.1944	0.1944
AF-05	DoD	0.0873	0.0873	0.0873
AG-01	GWA	0.0827	0.0827	0.0827
AG-02	GWA	0.6460	0.6460	0.6460
HGC-02	Private	0.7413	0.7413	0.7413
HGC-03	Private	0.0983	0.0983	0.0983
NCS-11	DoD	0.2162	0.2162	0.2162
NCS-12	DoD	0.2218	0.2218	0.2218
Total		**2.9280**	**2.9280**	**2.9280**
		Andersen basin		
BPM	DoD	0.0542	0.0542	0.0542
Y-15	GWA	0.7878	0.7878	0.7878
Total		**0.8420**	**0.8420**	**0.8420**
		Finegayan basin		
D-24	GWA	0.2664	**0.2664**	**0**
F-01	GWA	0.1584	**0.1584**	0.1584
F-02	GWA	0.1788	**0.1788**	**0**
F-03	GWA	0.2247	0.2247	0.2247
F-04	GWA	0.2110	**0.2110**	**0**
F-05	GWA	0.2784	0.2784	0.2784
F-06	GWA	**0.3312**	**0.3312**	**0**
F-07	GWA	0.2680	0.2680	0.2680
F-08	GWA	0.1655	0.1655	0.1655
F-09	GWA	0.1933	0.1933	0.1933
F-10	GWA	0.2726	**0.2726**	**0**
F-11	GWA	0.2420	**0.2420**	**0**
F-12	GWA	0.2856	0.2856	0.2856
F-13	GWA	0.2714	**0.2714**	**0**
F-15	GWA	0.3096	0.3096	0.3096

Table 4. Selected wells and withdrawal rates used in calibration and drought scenarios, Northern Guam Lens Aquifer, Guam.—Continued

[Values in pink or **red** represent wells with salinity in the cautionary or **threatened** range, respectively; cautionary yield is the volume of withdrawn water that has a salinity roughly from 200 to 500 milligrams per liter of chloride; **threatened yield** is the volume of withdrawn water that has a salinity greater than roughly 500 milligrams per liter of chloride; well information and withdrawal rates provided by Guam Water Authority (GWA), Department of Defense (DoD), and Guam Environmental Protection Agency; modeled salinity is the average salinity from all of the nodes representing each pumped well]

Well name	Well owner	Withdrawal rate (million gallons per day)		
		Average 2010	Drought	Drought-reduced withdrawal
F-16	GWA	0.4114	0.4114	0.4114
F-17	GWA	0.3058	0.3058	0.3058
F-19	GWA	0.1797	**0.1797**	**0**
F-20	GWA	0.2408	**0.2408**	**0**
H-01	GWA	0.3916	**0.3916**	**0**
NCS-06	DoD	0.2228	0.2228	0.2228
NCS-07	DoD	0.2256	0.2256	**0.2256**
NCS-09	DoD	0.2790	0.2790	0.2790
NCS-10	DoD	0.2032	**0.2032**	0.2032
NCS-A	DoD	0	**0**	**0**
NCS-B	DoD	0	0	0
Total		**6.1168**	**6.1168**	**3.5313**
		Hagåtña basin		
A-01	GWA	0.1168	0.1168	0.1168
A-02	GWA	0.2025	0.2025	0.2025
A-03	GWA	0.1298	0.1298	0.1298
A-04	GWA	0.4420	0.4420	0.4420
A-05	GWA	0.3854	0.3854	0.3854
A-06	GWA	0.4597	0.4597	0.4597
A-08	GWA	0.3752	0.3752	0.3752
A-09	GWA	0.3230	**0.3230**	0.0808
A-10	GWA	**0.4094**	**0.4094**	0.1024
A-12	GWA	0.2333	0.2333	**0.2333**
A-13	GWA	**0.4584**	**0.4584**	0
A-14	GWA	0.2059	0.2059	0.2059
A-15	GWA	0.4329	**0.4329**	0.3935
A-17	GWA	**0.3575**	**0.3575**	0
A-18	GWA	0.3456	**0.3456**	0.3142
A-19	GWA	0.2353	0.2353	0.2353
A-21	GWA	0.4002	**0.4002**	0.1001
A-23	GWA	0.4583	**0.4583**	0
A-25	GWA	0.4829	0.4829	0.4829
A-26	GWA	0.0689	0.0689	0.0689

Table 4. Selected wells and withdrawal rates used in calibration and drought scenarios, Northern Guam Lens Aquifer, Guam.—Continued

[Values in pink or red represent wells with salinity in the cautionary or threatened range, respectively; cautionary yield is the volume of withdrawn water that has a salinity roughly from 200 to 500 milligrams per liter of chloride; threatened yield is the volume of withdrawn water that has a salinity greater than roughly 500 milligrams per liter of chloride; well information and withdrawal rates provided by Guam Water Authority (GWA), Department of Defense (DoD), and Guam Environmental Protection Agency; modeled salinity is the average salinity from all of the nodes representing each pumped well]

Well name	Well owner	Withdrawal rate (million gallons per day)		
		Average 2010	Drought	Drought-reduced withdrawal
A-30	GWA	0.9671	**0.9671**	0.7253
A-31	GWA	0.4360	0.4360	0.4360
A-32	GWA	**0.3286**	**0.3286**	0
FFH-01–08	Private	**0.4365**	**0.4365**	**0.4365**
HRP-01	Private	0.0951	0.0951	0.0951
HRP-02	Private	0.0783	0.0783	0.0783
NAS-01	GWA	0.3728	0.3728	0.3728
NRMC-01	DoD	**0.1795**	**0.1795**	0
NRMC-02	DoD	**0.1560**	**0.1560**	0
NRMC-03	DoD	**0.0001**	**0.0001**	**0**
Total		**9.5720**	**9.5729**	**6.4727**
Mangilao basin				
EX-11	GWA	0.3322	0.3322	0.3322
M-01	GWA	0.2233	0.2233	0.2233
M-02	GWA	0.2573	0.2573	0.2573
M-03	GWA	0.3515	0.3515	0.3515
M-04	GWA	0.3604	**0.3604**	0
M-08	GWA	0.2036	0.2036	0.2036
M-09	GWA	0.0667	**0.0667**	**0**
M-23	GWA	0.3739	0.3739	0.3739
MGC-04	Private	0.0001	**0.0001**	**0.0001**
Total		**2.1690**	**2.1690**	**1.7419**
Yigo-Tumon basin				
D-01	GWA	0.3422	0.3422	0.3422
D-02	GWA	0.3032	0.3032	0.3032
D-04	GWA	0.3551	0.3551	0.3551
D-05	GWA	0.2439	0.2439	0.2439
D-06	GWA	0.3710	0.3710	0.3710
D-07	GWA	0.3041	**0.3041**	0.3041
D-08	GWA	0.2324	**0.2324**	**0**
D-09	GWA	0.2948	**0.2948**	**0**
D-10	GWA	0.3357	0.3357	0.3357
D-11	GWA	0.2157	0.2157	0.2157

Table 4. Selected wells and withdrawal rates used in calibration and drought scenarios, Northern Guam Lens Aquifer, Guam.—Continued

[Values in pink or **red** represent wells with salinity in the cautionary or **threatened** range, respectively; cautionary yield is the volume of withdrawn water that has a salinity roughly from 200 to 500 milligrams per liter of chloride; **threatened yield** is the volume of withdrawn water that has a salinity greater than roughly 500 milligrams per liter of chloride; well information and withdrawal rates provided by Guam Water Authority (GWA), Department of Defense (DoD), and Guam Environmental Protection Agency; modeled salinity is the average salinity from all of the nodes representing each pumped well]

Well name	Well owner	Withdrawal rate (million gallons per day)		
		Average 2010	Drought	Drought-reduced withdrawal
D-12	GWA	0.2795	0.2795	0.2795
D-13	GWA	**0**	**0**	**0**
D-14	GWA	0.3547	**0.3547**	0.3225
D-15	GWA	0.3378	0.3378	0.3378
D-16	GWA	0.3456	0.3456	0.3456
D-19	GWA	0.2779	0.2779	0.2779
D-20	GWA	0.3048	0.3048	0.3048
D-21	GWA	0.2833	0.2833	0.2833
D-25	GWA	0.4546	0.4546	0.4546
D-26	GWA	0.3281	**0.3281**	**0**
D-27	GWA	0.5568	0.5568	0.5568
D-28	GWA	0.2569	0.2569	0.2569
EX-05A	GWA	0.5442	0.5442	0.5442
FM-01	Private	0.0515	0.0515	0.0515
GH-501	GWA	0.3148	**0.3148**	**0**
GPH	Private	0.0455	**0.0455**	**0.0455**
M-05	GWA	0.3211	0.3211	0.3211
M-06	GWA	0.2355	**0.2355**	**0**
M-07	GWA	0.3143	0.3143	0.3143
M-12	GWA	0.1168	**0.1168**	0
M-15	GWA	0.3242	0.3242	0.3242
M-17B	GWA	0.4238	0.4238	0.4238
M-18	GWA	0.3439	0.3439	0.3439
M-20A	GWA	0.4050	0.4050	0.4050
M-21	GWA	0.4857	0.4857	0.4415
MW-01	DoD	0.0466	0.0466	0.0466
MW-03	DoD	0.0329	0.0329	0.0329
MW-05	DoD	0.1789	**0.1789**	0.0447
MW-06	DoD	0.4032	**0.4032**	0.2016
MW-07	DoD	0.2296	0.2296	0.2296
MW-08	DoD	0.5362	0.5362	0.5362
MW-09	DoD	0.3538	0.3538	0.3538
PBI-01	Private	0.0113	0.0113	0.0113

Table 4. Selected wells and withdrawal rates used in calibration and drought scenarios, Northern Guam Lens Aquifer, Guam.—Continued

[Values in pink or red represent wells with salinity in the cautionary or threatened range, respectively; cautionary yield is the volume of withdrawn water that has a salinity roughly from 200 to 500 milligrams per liter of chloride; threatened yield is the volume of withdrawn water that has a salinity greater than roughly 500 milligrams per liter of chloride; well information and withdrawal rates provided by Guam Water Authority (GWA), Department of Defense (DoD), and Guam Environmental Protection Agency; modeled salinity is the average salinity from all of the nodes representing each pumped well]

Well name	Well owner	Withdrawal rate (million gallons per day)		
		Average 2010	Drought	Drought-reduced withdrawal
PIC	Private	**0.2560**	**0.2560**	**0.2560**
TUMON	DoD	0	0	0
Y-01	GWA	0.2980	0.2980	0.2980
Y-02	GWA	0.2640	**0.2640**	**0.2640**
Y-03	GWA	0.2843	0.2843	0.2843
Y-04	GWA	0.3046	**0.3046**	**0.3046**
Y-05	GWA	0.2938	**0.2938**	**0.2938**
Y-06	GWA	0.3093	**0.3093**	**0.3093**
Y-07	GWA	0.2541	0.2541	0.2541
Y-09	GWA	0.5427	0.5427	0.5427
Y-10	GWA	0.2759	**0.2759**	**0.2759**
Y-12	GWA	0.4595	**0.4595**	**0.4595**
Y-14	GWA	0.4915	**0.4915**	**0.4915**
Y-16	GWA	0.4446	**0.4446**	**0.4446**
Y-17	GWA	0.4657	0.4657	0.4657
Y-18	GWA	0.4292	**0.4292**	**0.4292**
Y-19	GWA	0.6412	**0.6412**	**0.6412**
Y-20	GWA	0.9132	**0.9132**	**0.9132**
Y-21	GWA	0.2682	**0.2682**	**0.2682**
Y-22	GWA	0.3643	**0.3643**	**0.3643**
Y-23	GWA	0.4105	0.4105	0.4105
Total		**20.4673**	**20.4673**	**18.5329**

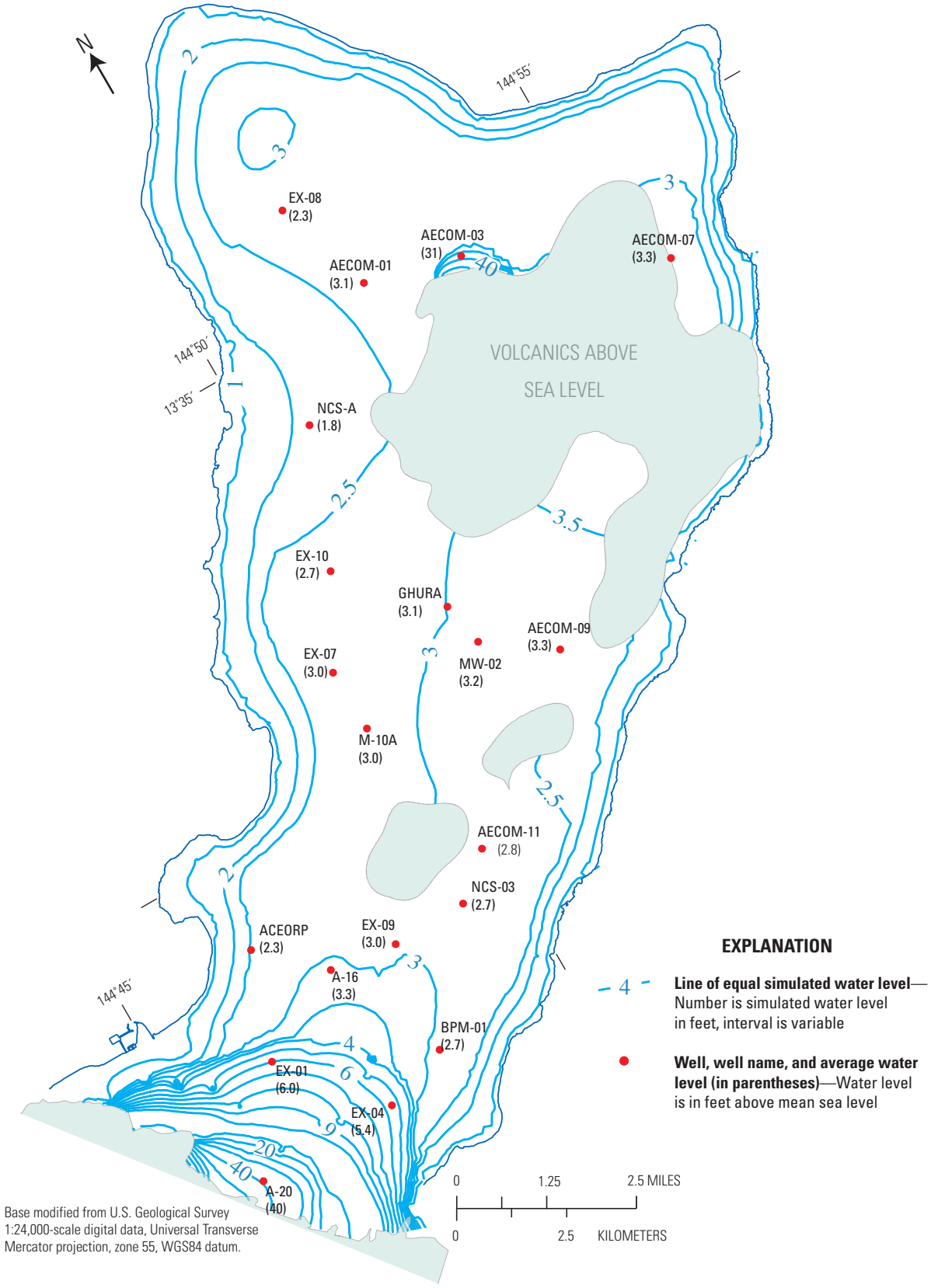


Figure 14. Measured and simulated water levels in selected wells in the Northern Guam Lens Aquifer, Guam.

Salinity in Wells

Pumped Wells

Simulated equivalent chloride concentrations at pumped wells generally are in agreement with measured chloride concentrations of the pumped water (fig. 15). Measured chloride concentration values were obtained from various GWA, DoD, and GEPA records. Simulated equivalent chloride concentrations were converted from simulated salinity values by dividing the salinity value (expressed as a percentage of seawater) by 100 and multiplying the result by the assumed seawater chloride concentration (19,600 mg/L). Simulated salinity values are a flow-weighted average of all nodes representing the well. In some wells, the number of nodes representing the well was increased or decreased to more accurately match the measured salinity. These adjustments were justified in many cases where the well construction may have changed over time or the pump may be drawing water from only a fraction of the well's open interval.

Wells in which the simulated equivalent chloride concentration does not match the measured chloride concentration reasonably are labeled in fig. 15. In most cases, the model underestimates the chloride concentration in these wells. This is most likely because the wells are very near the inland model boundaries where the limestone aquifer is thin and the model may not be accurately representing the complex geology where the limestone meets the underlying volcanic basement. Two wells (D08, D13), which are fairly distant from the limestone/volcanic basement contact (locations shown on fig. 12), have traditionally had high chloride concentrations (fig. 16*A*). The model does not accurately reproduce the measured values because the geology near these wells likely is more complicated than represented in the model. Additional study is needed to determine the local geologic structure that contributes to the persistent high salinities observed in these wells.

Classifications for the simulated salinity at selected pumped wells discussed in this report are (1) acceptable, chloride concentration less than 200 mg/L (less than about 1.0 percent seawater; (2) cautionary, chloride between 200 and 500 mg/L (between 1.0 and 2.6 percent seawater); and (3) threatened, chloride concentration greater than 500 mg/L (greater than 2.6 percent seawater). These categories are roughly in line with the secondary drinking water standard for chloride of 250 mg/L (Guam Environmental Protection Agency, 2001). Water in the acceptable category is expected to be below the standard, water in the cautionary category is near or above the standard but could be blended with fresher water to meet the standard, and water in the threatened category is well above the standard. Wells with simulated salinity in the threatened class are likely to produce water unacceptable for drinking or that would require substantial blending. This classification was developed for several studies on Maui, Hawai‘i, as a basis for comparing the various scenarios investigated (Gingerich, 2008; Gingerich and Engott, 2012). The simulated salinities are the weighted average salinity of all nodes representing each well's open interval. Private wells that develop water for irrigation, aquaculture, construction, and other non-drinking-water uses were not included in this classification. For this report, drinking-water wells refers to GWA and DoD wells, which produce water primarily used for drinking and other domestic uses.

Salinity Profiles

The shapes of the simulated salinity profiles are generally consistent with the measured profiles (fig. 17). Simulated and measured depths where salinity is 50 percent that of seawater are within 2–23 ft of each other. In most of the wells, the simulated salinity profiles are broader and smoother than the measured profiles, indicating that the model is simulating more dispersion than is warranted. The profiles would possibly match better with lower transverse dispersivity values in the model or finer vertical mesh discretization. However, modeled dispersivity values cannot be set any lower without generating significant numerical dispersion, and a finer mesh would lead to model run times that are too impractical for this study. Overall, the match between simulated and measured salinity profiles is considered sufficient for the study purposes.

Some of the discrepancy between measured and simulated salinity profiles could also be attributed to possible borehole flow in the deep monitoring wells (Paillet and others, 2002; Rotzoll, 2010) and additional factors described above for simulated water levels; however, the incidence and magnitude of borehole flow in wells on Guam has yet to be documented. Borehole flow in the deep monitoring wells could cause a lack of agreement between the simulated and measured profiles. The simulated profile is from simulated salinity values in the aquifer, whereas the measured profile is influenced by the water level in the open well or borehole, which (because of the vertical hydraulic connection created by the open borehole and the accompanying intraborehole flow) represents a composite head in the aquifer interval penetrated by the well. For example, the measured salinity profile for well EX-4 shows an abrupt increase in salinity at about –240 ft rather than a smooth increase in salinity with depth (fig. 17). Rotzoll (2010) demonstrates that this sort of step in the profile is indicative of borehole flow affecting the measured profile; however, without downhole flow measurements, it is not possible to determine definitively which direction the water is flowing.

The freshwater lens (less than 500 mg/L chloride concentration or about 2.6-percent seawater salinity) in the NGLA is thickest where aquifer hydraulic conductivity is the lowest and in parts of the aquifer farthest from the coast (fig. 18). The southern part of the Hagåtña basin has an area of freshwater more than 200 ft thick that is penetrated by many of the A-series wells (fig. 12). This area corresponds to the location of the Argillaceous Limestone, where the hydraulic conductivity is more than 10 times lower than the limestone to the north. Two areas of lower hydraulic conductivity allow a thicker freshwater lens to develop in parts of the Agafo Gumas basin. The freshwater lens is greater than 200 ft thick in the

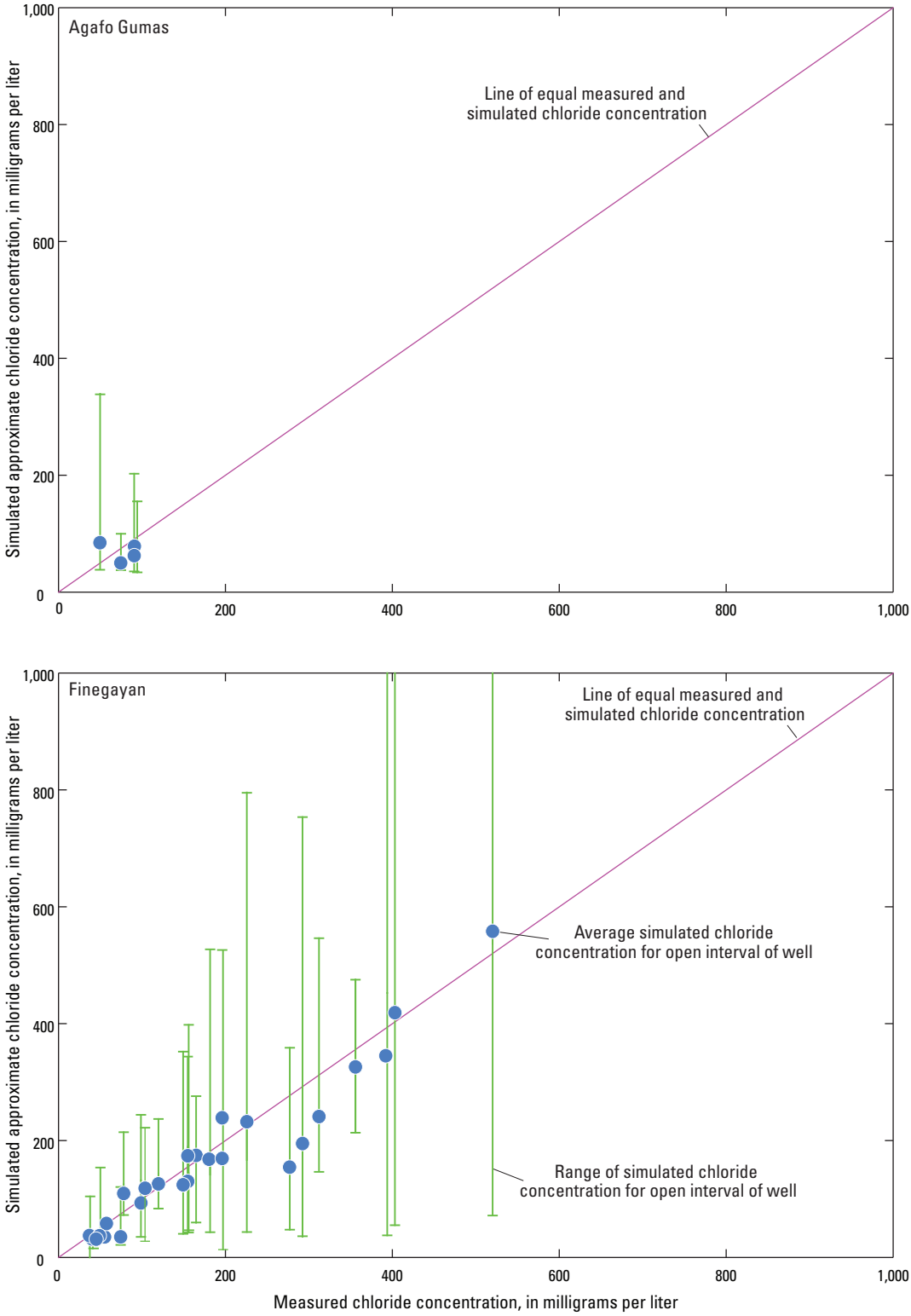


Figure 15. Relation between measured and simulated approximate chloride concentration in selected wells in the Northern Guam Lens Aquifer, Guam, by aquifer basin.

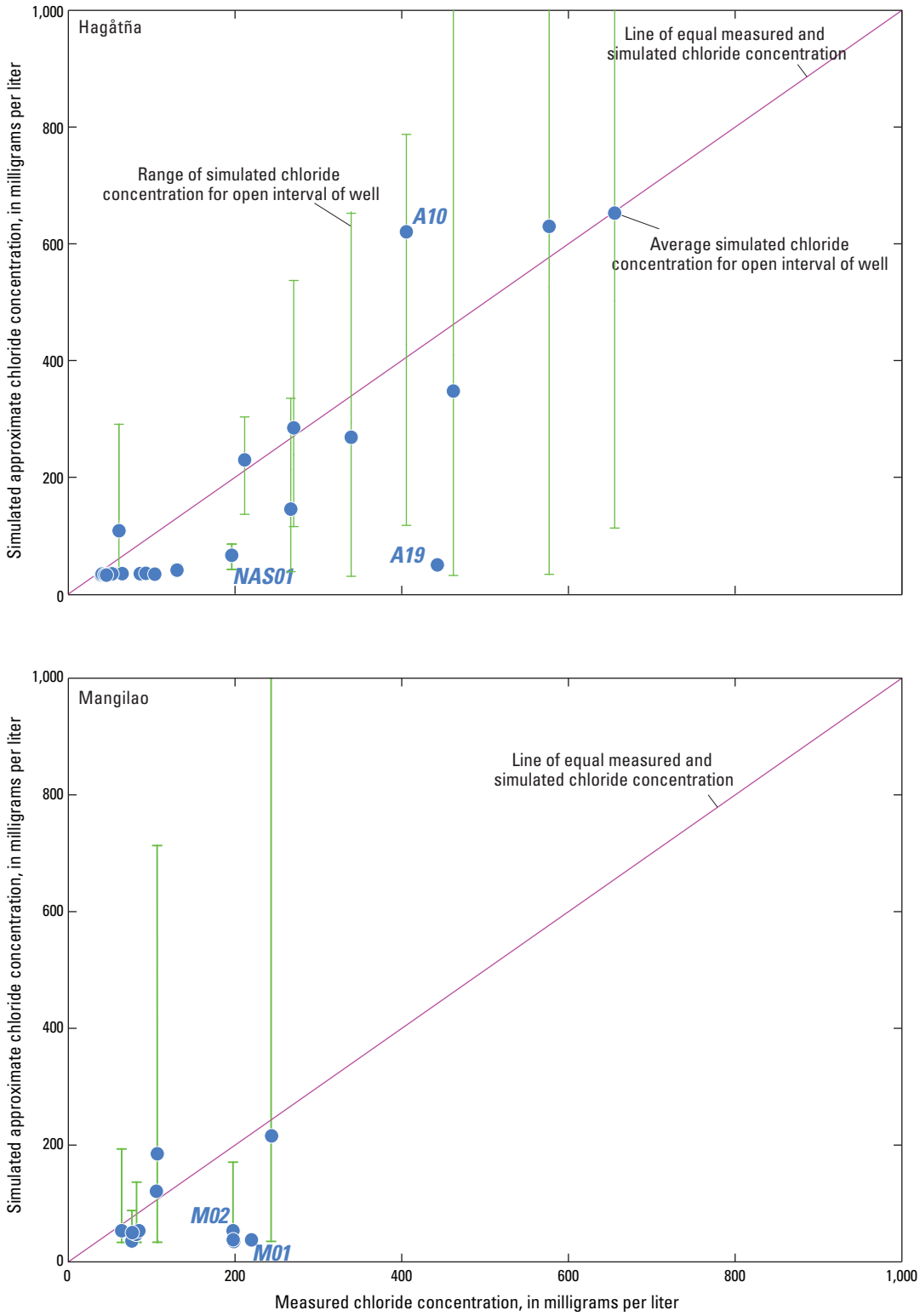


Figure 15. Relation between measured and simulated approximate chloride concentration in selected wells in the Northern Guam Lens Aquifer, Guam, by aquifer basin.—Continued

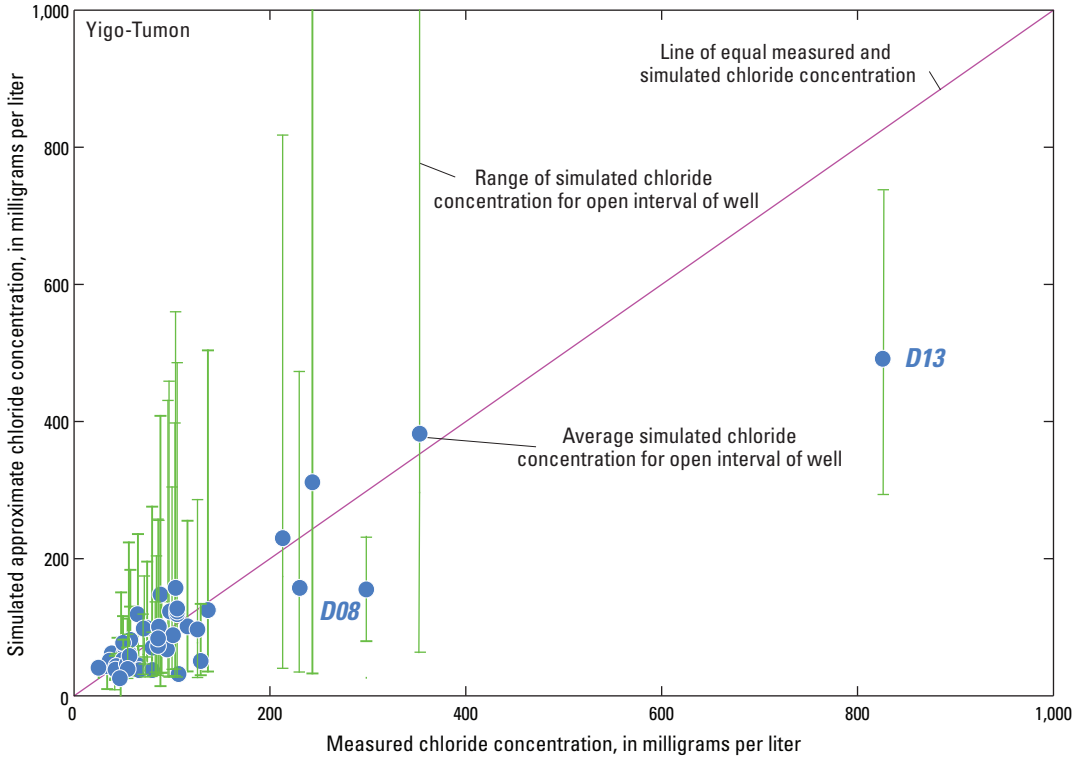


Figure 15. Relation between measured and simulated approximate chloride concentration in selected wells in the Northern Guam Lens Aquifer, Guam, by aquifer basin.—Continued

small area of low hydraulic conductivity that causes the high water level observed in well AECOM-03 (fig. 14). The lens is also more than 100 ft thick in the low-hydraulic-conductivity rocks northwest of well EX-08. No field observations are available to confirm that the model is accurately representing the groundwater conditions in these areas. The freshwater lens is expected to be more than 100 ft thick in the interior part of the Yigo-Tumon basin farthest from the western coast. Many of the Y-series wells (fig. 12) penetrate this part of the freshwater lens.

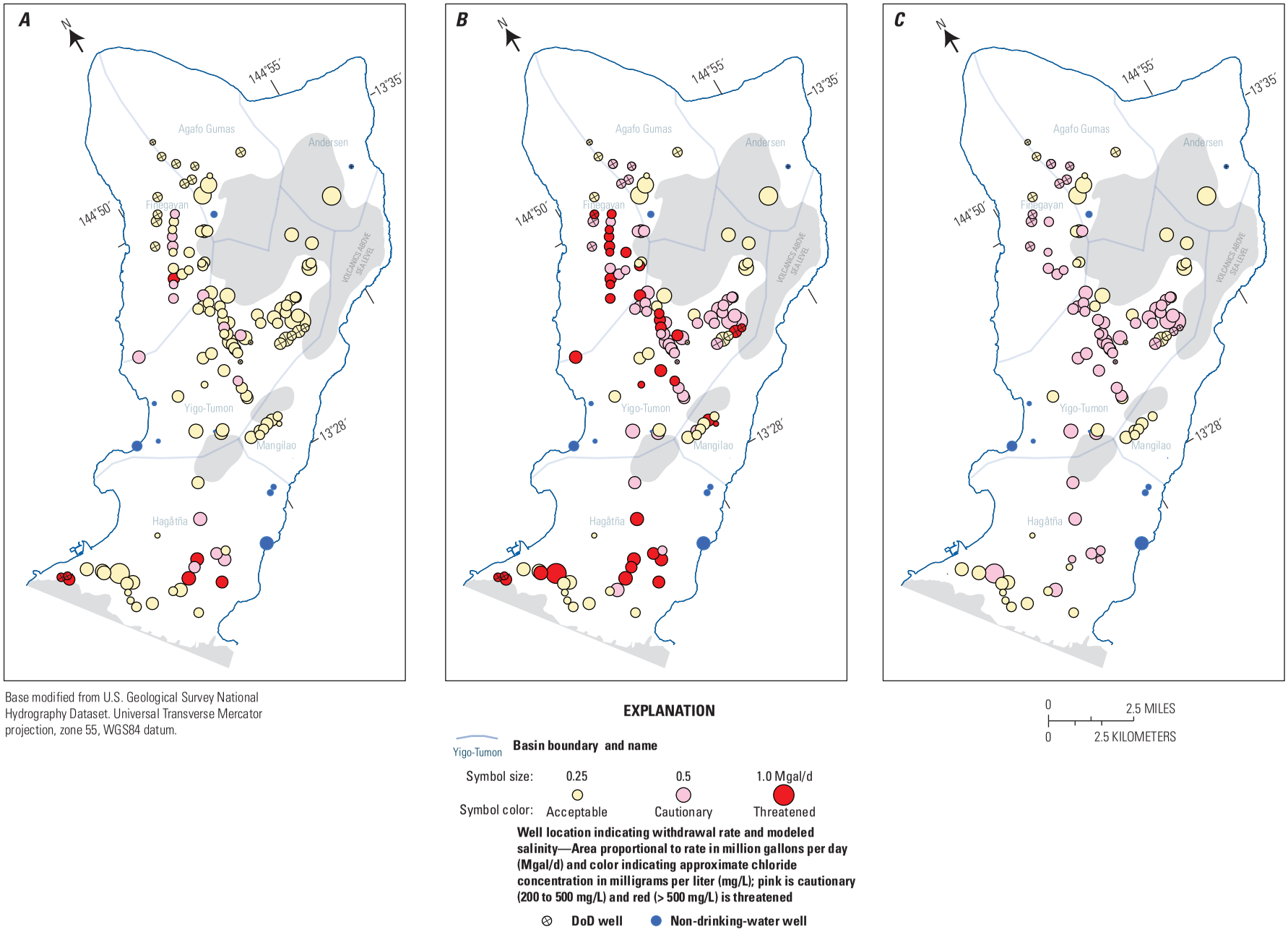
The freshwater lens is thinnest around the island's periphery and around the volcanics where they are above sea level (fig 18.). Much of the Finegayan basin has a thin freshwater lens due to the highly permeable aquifer in this area that allows a better connection to the coast. Many of the NCS- and F-series wells in this area experience salinity problems (fig. 9).

Coastal Discharge of Fresh Groundwater

The calibrated numerical model was used to estimate the distribution of fresh groundwater discharge to the coast for current conditions (average recharge during 1961–2005 and 2010 withdrawal conditions). Total simulated coastal discharge of freshwater from the NGLA is about 163 Mgal/d. Coastal groundwater discharge is calculated from the SUTRA model output by summing the freshwater flux (total water flux multiplied by percentage freshwater fluid concentration) leaving each specified-pressure node along the coast. Discharge estimates are presented with arrows that are sized proportionally on the basis of discharge volume for each mile of coastline around northern Guam (fig. 19). Estimated discharge ranges from 0.6 to 17.8 Mgal/d per mile of coastline. The areas of highest simulated freshwater discharge are at Haputo Bay and Tumon Bay. In the model, discharge from the 6 mi of coast along Haputo and Tumon Bays (fig. 1) is about 37 percent of the entire discharge along the 44 mi of northern Guam's coast, even though these two areas represent only about 14 percent of the entire length of the coastline. This finding matches the discharge pattern described by Jocson and others (1999), who estimated 5–9 Mgal/d of discharge per mile of coastline in Tumon and Haputo Bay based on measurements of the most visible features. The abundant occurrence of springs and seeps described by Taboroši and others (2013) corresponds with the areas of highest discharge predicted by the groundwater model. The groundwater flow patterns predicted by the model indicated that groundwater flows from the Agafo Gumas, Finegayan, and Yigo-Tumon basins to discharge in this area (fig. 19). These flow patterns were noted by Vann and others (2013) when they proposed modifications to the basin boundaries.

Groundwater Conditions Before Pumping

The numerical model constructed for this study was used to estimate the changes in groundwater level and salinity between predevelopment (no pumping) and 2010 conditions.



Base modified from U.S. Geological Survey National Hydrography Dataset. Universal Transverse Mercator projection, zone 55, WGS84 datum.

EXPLANATION

Yigo-Tumon **Basin boundary and name**

Symbol size: 0.25 0.5 1.0 Mgal/d

Symbol color: Acceptable Cautionary Threatened

Well location indicating withdrawal rate and modeled salinity—Area proportional to rate in million gallons per day (Mgal/d) and color indicating approximate chloride concentration in milligrams per liter (mg/L); pink is cautionary (200 to 500 mg/L) and red (> 500 mg/L) is threatened

DoD well **Non-drinking-water well**

Figure 16. Simulated salinity at pumped wells in the Northern Guam Lens Aquifer, Guam. *A*, average 2010. *B*, 5-year drought. *C*, drought conditions with reduced withdrawal.

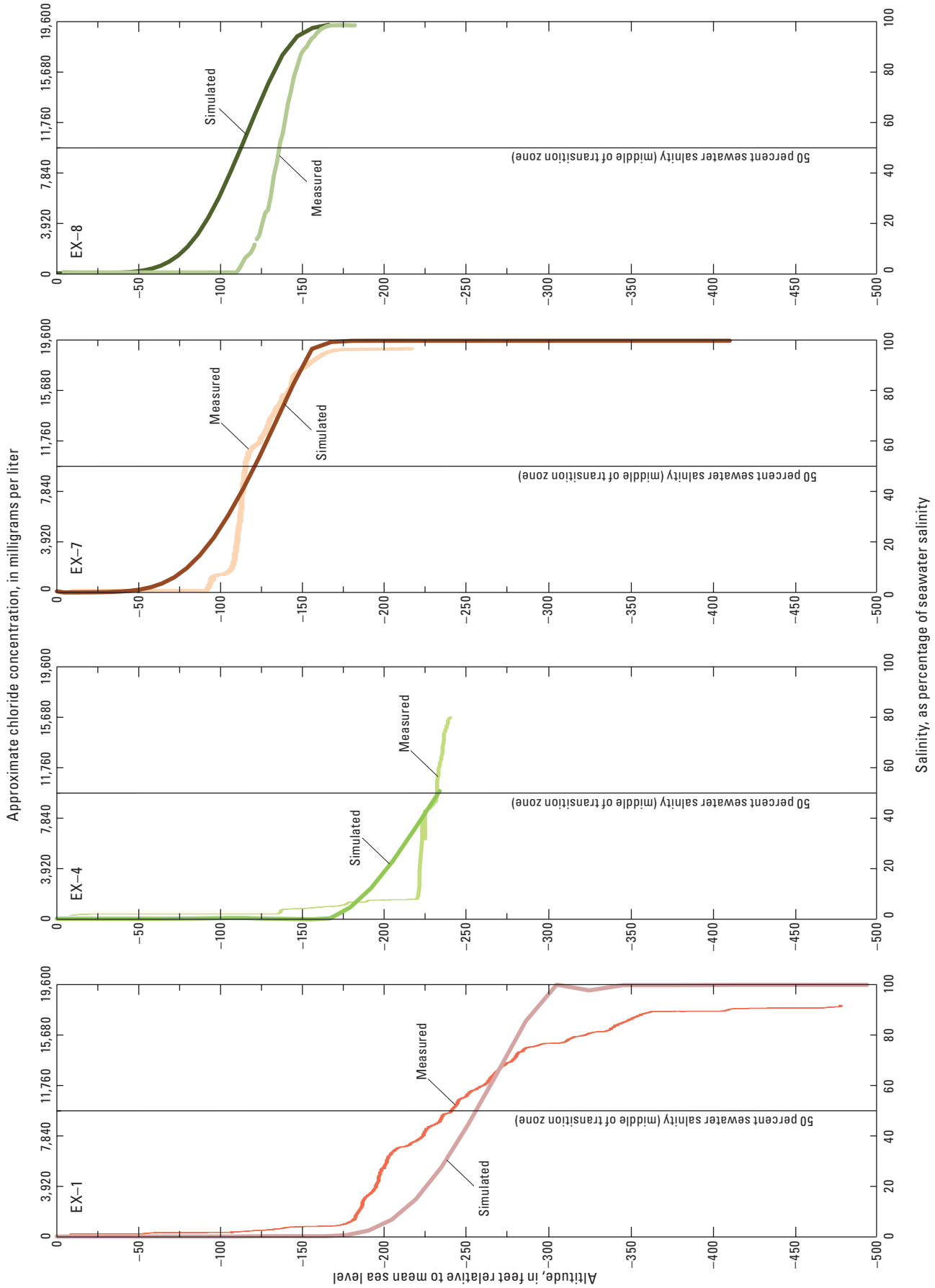


Figure 17. Measured and simulated salinity profiles in selected monitoring wells in the Northern Guam Lens Aquifer, Guam.

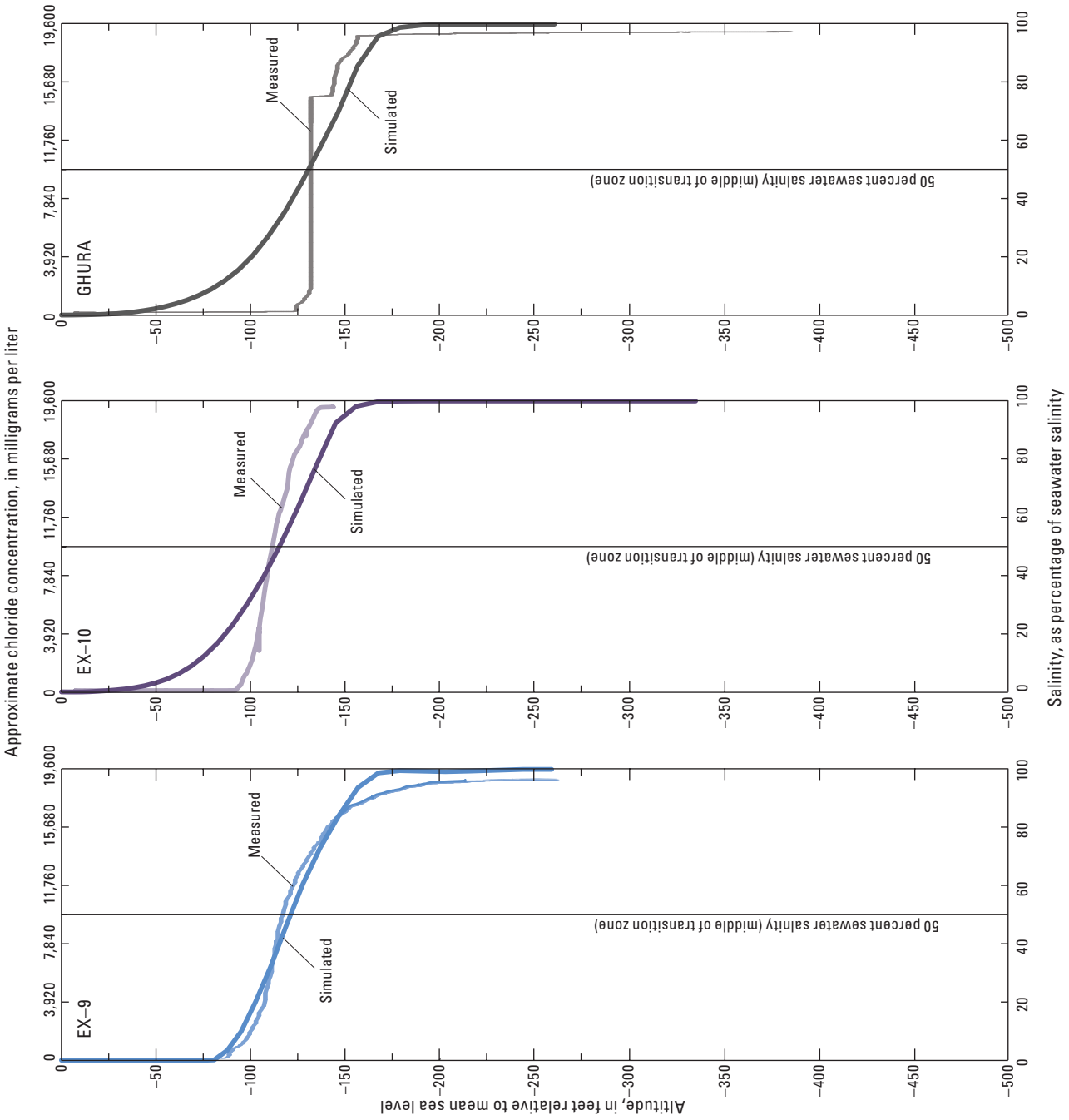


Figure 17. Measured and simulated salinity profiles in selected monitoring wells in the Northern Guam Lens Aquifer, Guam.—Continued

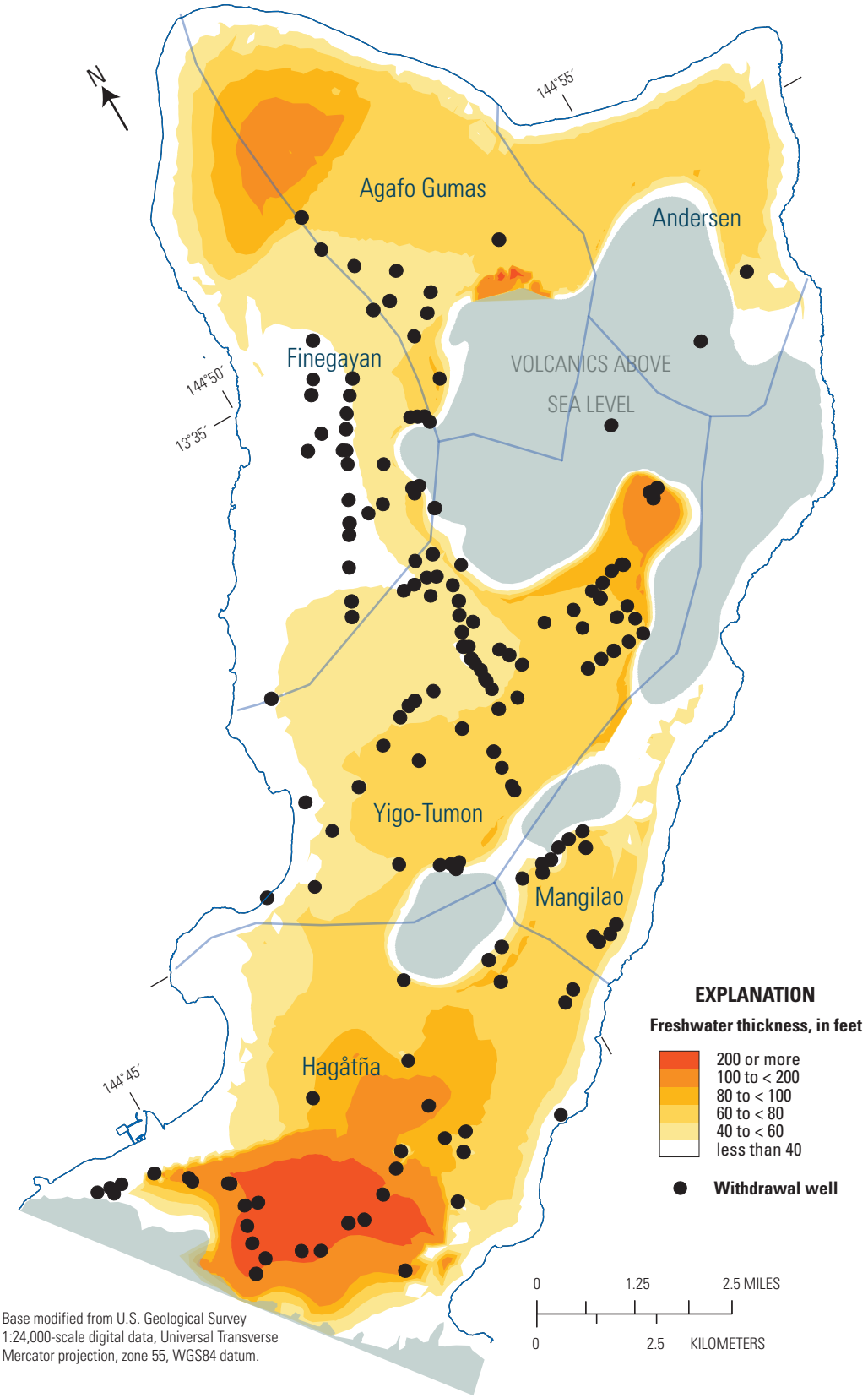


Figure 18. Simulated freshwater thickness in the Northern Guam Lens Aquifer, Guam.

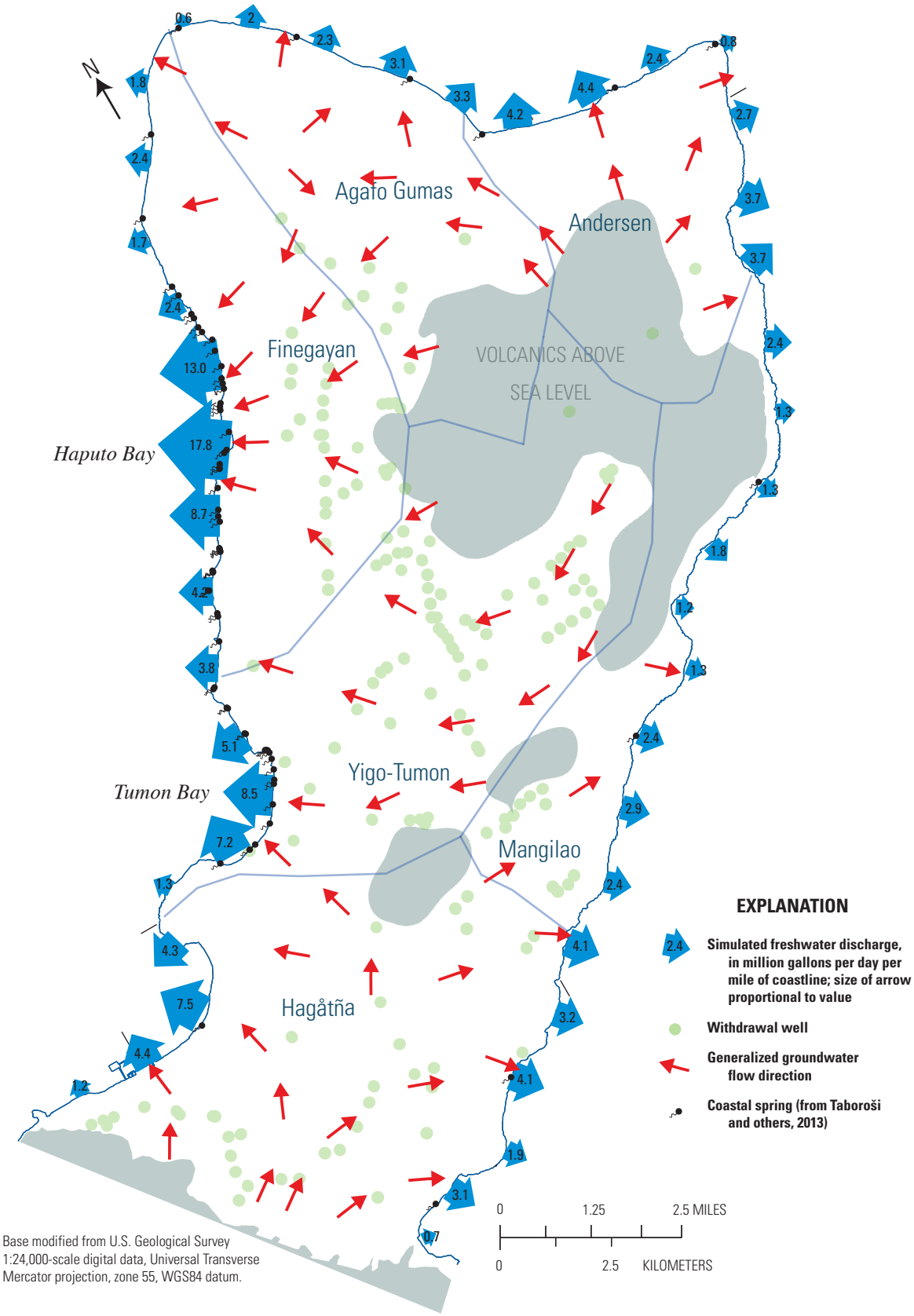


Figure 19. Simulated freshwater discharge from the Northern Guam Lens Aquifer, Guam.

For this scenario, no groundwater withdrawal was simulated, and because a predevelopment estimate for recharge was not available, recharge was based on the same rainfall and land use as in the calibrated model (table 2). The difference between actual predevelopment recharge and the recharge used here to evaluate no-pumping conditions was not quantified but was not considered necessary to evaluate the effects of groundwater withdrawals on the groundwater system. During simulation of predevelopment conditions, recharge from septic fields, leaky water mains, and irrigation was neglected; the total of these contributions is only about 12 Mgal/d of water to an overall recharge estimate for northern Guam of about 238 Mgal/d (about 5 percent).

The simulated change in water level and freshwater-lens thickness[1] between predevelopment and current conditions is greatest in the Hagåtña basin, where the aquifer has a lower hydraulic conductivity (fig. 20). In this area, where freshwater in the limestone aquifer lies directly on the underlying volcanics, predevelopment water levels were more than 5 ft higher. Accordingly, the freshwater lens was more than 50 ft thicker where the volcanic basement is deeper and the aquifer is thick enough to accommodate the extra freshwater thickness (fig. 20). In the Yigo-Tumon basin, water levels were as much as 1 ft greater and the freshwater lens was thicker in most areas by 10–50 ft. Further north, in the Agafo Gumas basin, the salinity distribution is about the same during simulated predevelopment and 2010 conditions, confirmed by the slight differences in profiles at well EX-08 (fig. 21). This may indicate that the 2010 pumping rates in the Agafo Gumas basin were not high enough to cause a noticeable change in the freshwater-lens thickness.

Relative to predevelopment conditions, the simulated freshwater lens for current conditions shrank in response to groundwater withdrawal; therefore, the landward extent of the para-basal zone moved slightly seaward as the water table decreased, and the seaward extent moved landward as saltwater encroached farther up the slope of the underlying volcanics (fig. 22). Because of density effects in a freshwater lens, changes of the water table of about a foot would not cause much seaward movement of the landward extent of freshwater; however, the thickness of the freshwater would decrease by about 40 ft, causing a much greater landward movement of the seaward extent of para-basal water depending on the slope of the underlying volcanic basement rock. A shift of the most-seaward extent of the para-basal water by about 1,000 ft landward can be seen around much of the area where volcanics are above sea level. The greatest shift is in the northern part of the Yigo-Tumon basin, where the most-seaward extent of the zone of para-basal water moved more than 5,000 ft inland. In 10 locations, the para-basal zone is now landward of wells that were originally drilled into the para-basal zone and, therefore, the wells are now more vulnerable to salinity increases because pumping could induce flow from the saltwater that has encroached landward to lie below the well (fig. 6).

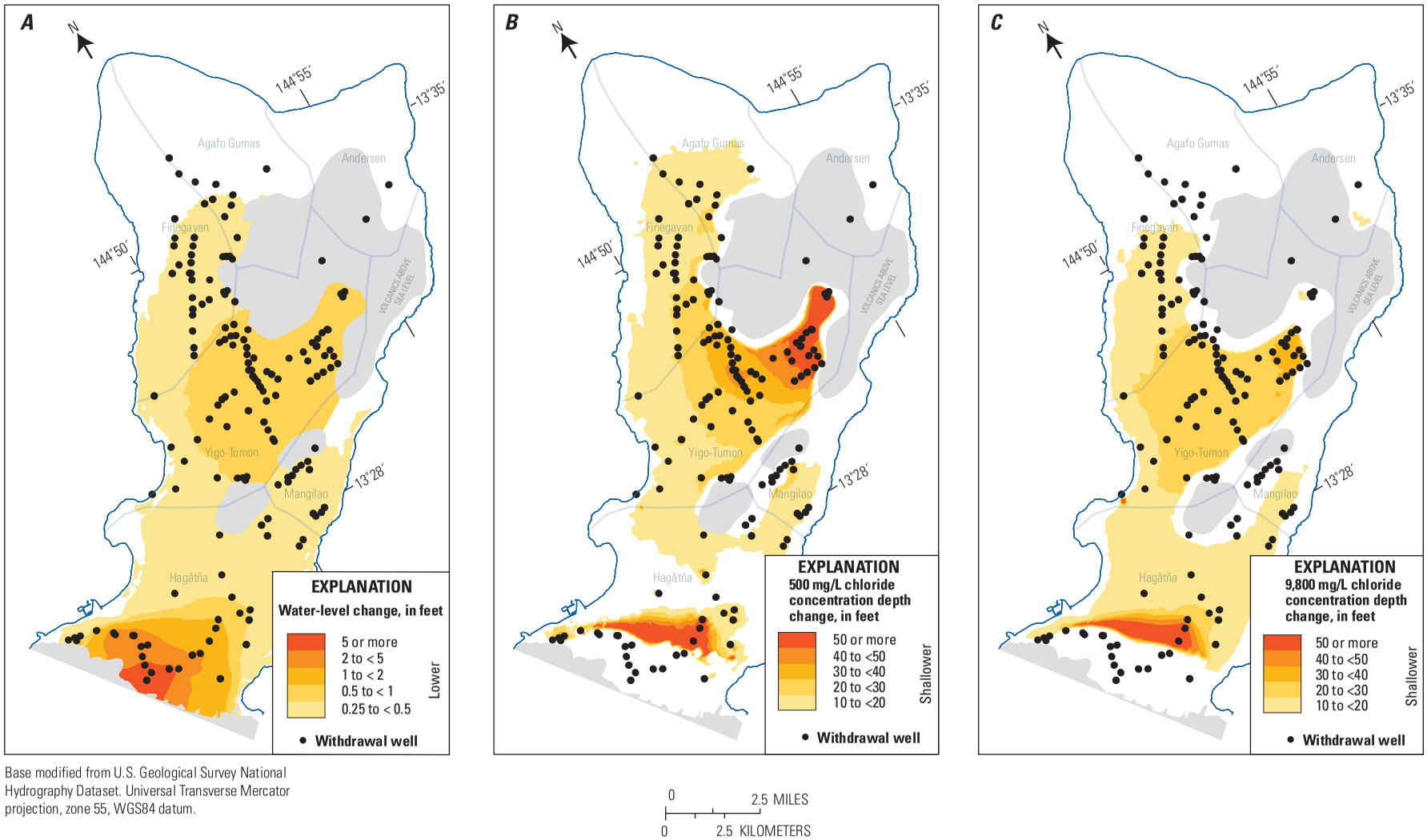
Drought Conditions

The effects of a 5-year drought on the 2010 pumping distribution were investigated with a simulation in which recharge over the model domain was reduced by 32 percent to 155 Mgal/d, based on the distribution estimated by Johnson (2012) using 1969–73 rainfall (table 3). The period 1969–73 had the lowest recorded rainfall for any 5-year period on Guam (Johnson, 2012). Withdrawal rates were the same as for average 2010 conditions for all wells (table 4). This scenario represents generalized conditions, because the decrease in recharge during the 5-year drought is imposed immediately and held constant over the 5-year period, and model results are presented for a 5-year transient transport simulation with constant pumping to meet all assumed demands.

Overall, withdrawal of 40.27 Mgal/d of drinking water from the NGLA after 5 years of the drought results in 17.77 Mgal/d of cautionary yield and 11.0 Mgal/d of threatened yield (fig. 16*B*), a total of about 71 percent of the entire withdrawal from the NGLA (table 5). The total water volume in the acceptable category is 11.5 Mgal/d. The Yigo-Tumon basin has the highest amount of combined cautionary (13.1 Mgal/d) and threatened (2.81 Mgal/d) yield; this amount represents about 79 percent of the total water pumped from the Yigo-Tumon basin. The Hagåtña basin has the second highest amount of combined cautionary (1.02 Mgal/d) and threatened (4.82 Mgal/d) yield; this amount represents about 65 percent of the total water pumped from this basin.

Plots of simulated salinity trends in pumped water from selected wells in the NGLA illustrate the salinity rise throughout the 5-year drought (fig. 23). After restoration of average recharge, salinities decrease relatively quickly and return to pre-drought conditions within 4–5 years.

[1] The position of the seaward extent of the para-basal zone was mapped by delineating where all water in contact with the aquifer base had a simulated chloride concentration less than 500 mg/L.



Base modified from U.S. Geological Survey National Hydrography Dataset. Universal Transverse Mercator projection, zone 55, WGS84 datum.

Figure 20. Simulated change (relative to predevelopment) for withdrawal at 2010 rates with long-term average recharge, Guam. *A*, Water level. *B*, 500 mg/L chloride concentration depth. *C*, 9,800 mg/L chloride concentration (50 percent seawater salinity) depth.

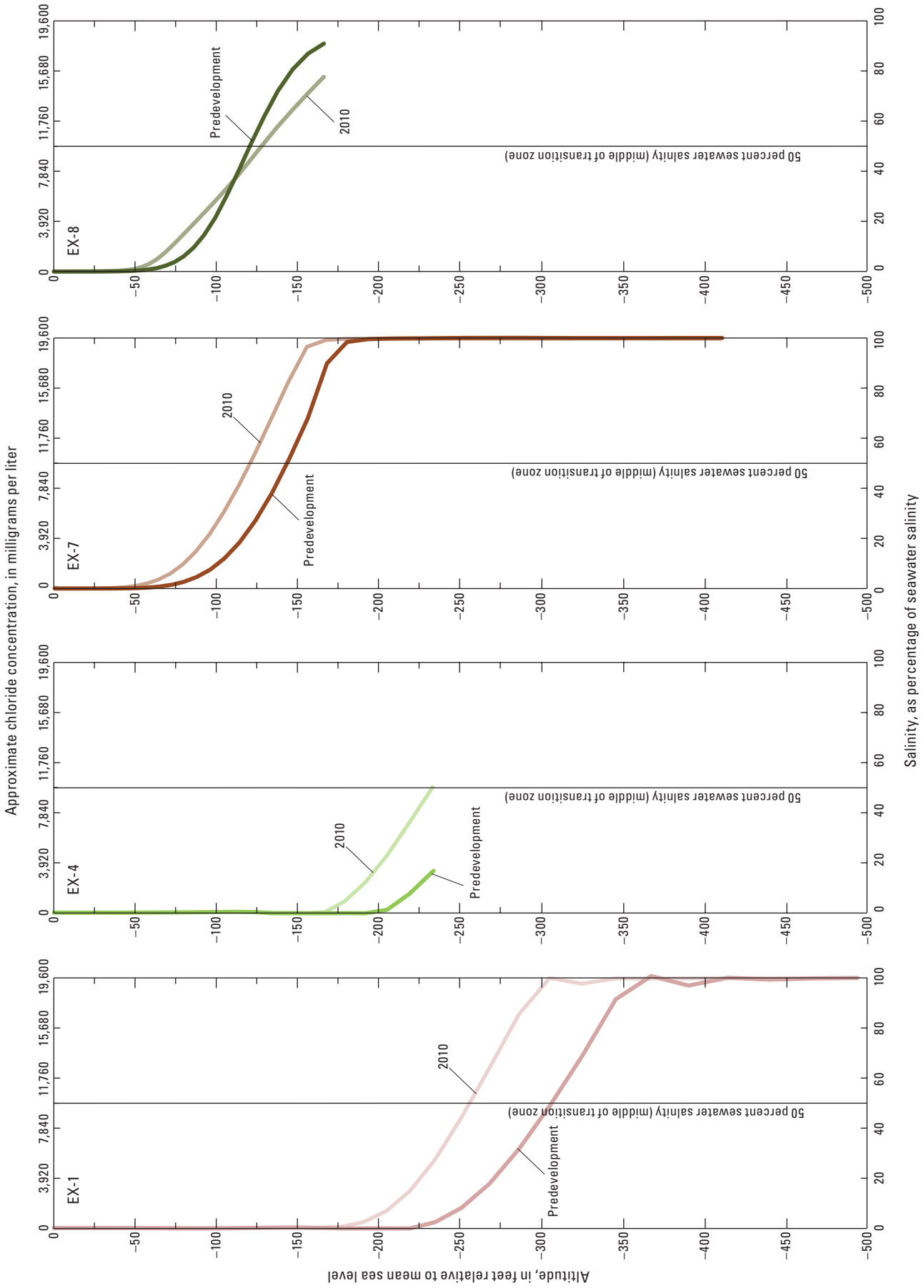


Figure 21. Simulated change (relative to predevelopment) in salinity profiles in selected deep monitoring wells, Northern Guam Lens Aquifer, Guam.

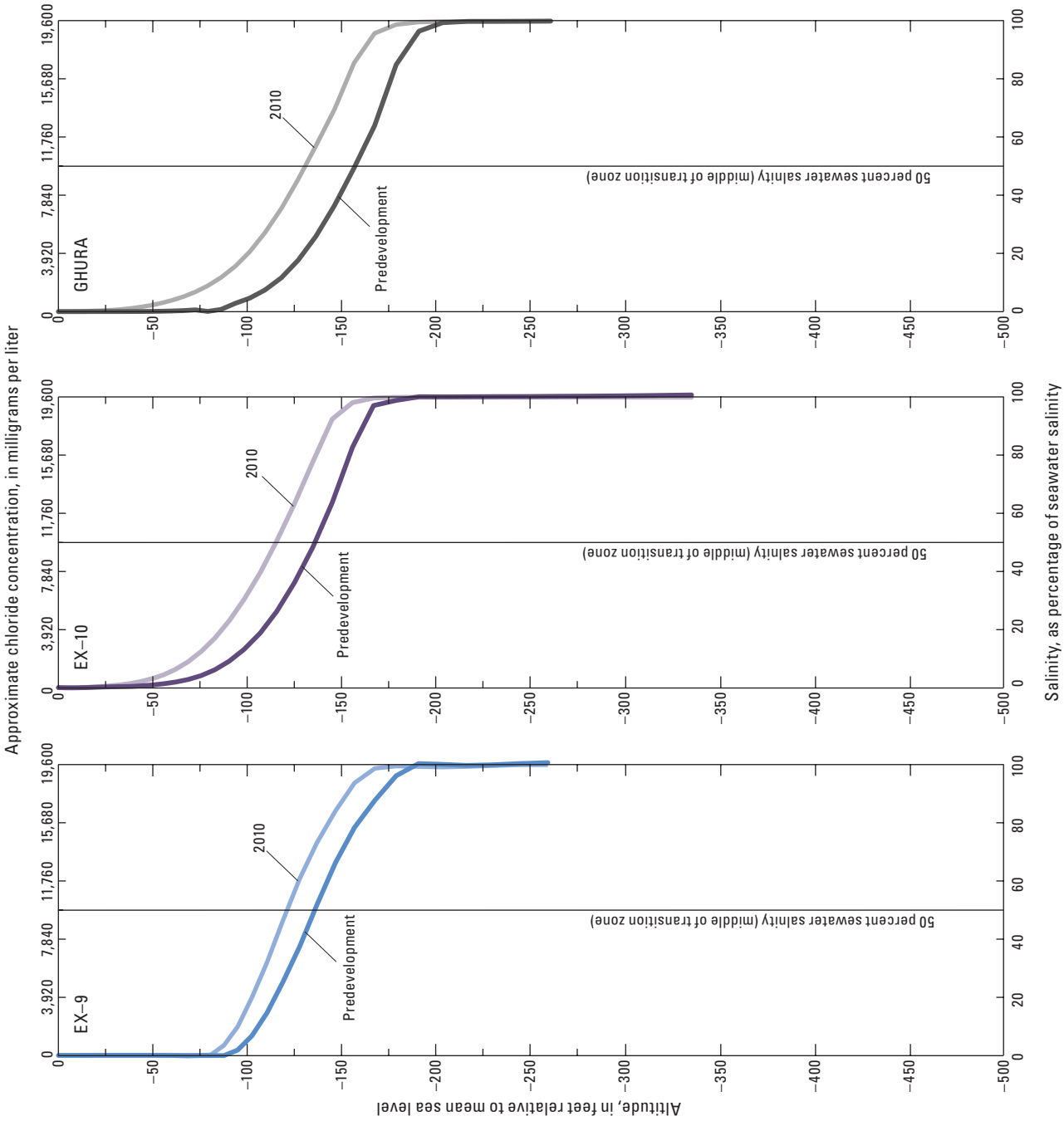


Figure 21. Simulated change (relative to predevelopment) in salinity profiles in selected deep monitoring wells, Northern Guam Lens Aquifer, Guam.—Continued

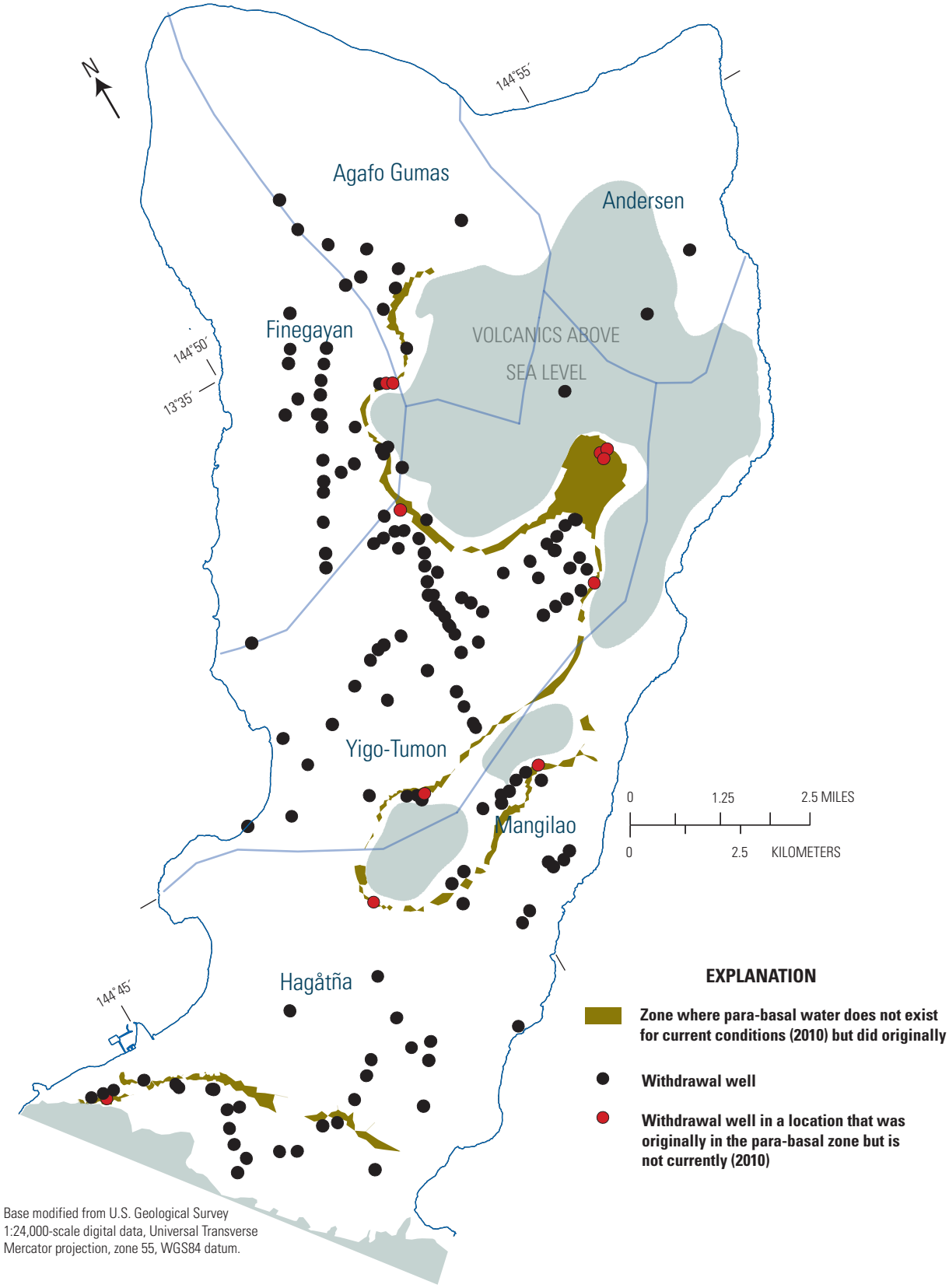


Figure 22. Simulated change (relative to predevelopment) in the position of the para-basal zone in the Northern Guam Lens Aquifer, Guam.

Table 5. Classification of withdrawal for simulated scenarios, Northern Guam Lens Aquifer, Guam.

[All results exclude non-drinking-water wells; GEPA, Guam Environmental Protection Agency; USMC, United States Marine Corps needs; cautionary yield is the volume of withdrawn water that has a salinity roughly from 200 to 500 milligrams per liter of chloride; threatened yield is the volume of withdrawn water that has a salinity greater than roughly 500 milligrams per liter of chloride; Mgal/d, million gallons per day]

Aquifer basin	GEPA 1991 sustainable yield estimate (Mgal/d)	Total simulated withdrawal (Mgal/d)	Cautionary withdrawal (Mgal/d)	Cautionary withdrawal (percent of total)	Threatened withdrawal (Mgal/d)	Threatened withdrawal (percent of total)
2010 average withdrawal						
Agafo Gumas	12	2.09	0	0	0	0
Andersen	10	0.79	0	0	0	0
Finegayan	12	6.12	1.81	30	0.33	5
Hagåtña	21	8.96	1.16	13	1.89	21
Mangilao	7	2.17	0	0	0	0
Yigo-Tumon	20	20.15	1.17	6	0	0
Total	**81**	**40.27**	**4.14**	**10**	**2.22**	**6**
5-year drought						
Agafo Gumas	12	2.09	0.83	40	0	0
Andersen	10	0.79	0	0	0	0
Finegayan	12	6.12	2.49	41	2.95	48
Hagåtña	21	8.96	1.02	11	4.82	54
Mangilao	7	2.17	0.33	15	0.43	20
Yigo-Tumon	20	20.15	13.10	65	2.81	14
Total	**81**	**40.28**	**17.77**	**44**	**11.01**	**27**
5-year drought–reduced withdrawal						
Agafo Gumas	12	2.09	0.83	40	0	0
Andersen	10	0.79	0	0	0	0
Finegayan	12	3.53	2.13	60	0	0
Hagåtña	21	5.86	2.66	45	0	0
Mangilao	7	1.74	0	0	0	0
Yigo-Tumon	20	18.17	13.26	73	0	0
Total	**81**	**32.18**	**18.88**	**59**	**0**	**0**
Scenario 1–Expected growth (non-USMC)						
Agafo Gumas	12	3.10	0	0	0	0
Andersen	10	0.79	0	0	0	0
Finegayan	12	6.16	1.18	19	0.71	12
Hagåtña	21	9.10	1.04	11	1.87	21
Mangilao	7	2.18	0	0	0	0
Yigo-Tumon	20	23.51	1.50	6	0	0
Total	**81**	**44.84**	**3.72**	**8**	**2.58**	**6**

Table 5. Classification of withdrawal for simulated scenarios, Northern Guam Lens Aquifer, Guam.—Continued

[All results exclude non-drinking-water wells; GEPA, Guam Environmental Protection Agency; USMC, United States Marine Corps needs; cautionary yield is the volume of withdrawn water that has a salinity roughly from 200 to 500 milligrams per liter of chloride; threatened yield is the volume of withdrawn water that has a salinity greater than roughly 500 milligrams per liter of chloride; Mgal/d, million gallons per day]

Aquifer basin	GEPA 1991 sustainable yield estimate (Mgal/d)	Total simulated withdrawal (Mgal/d)	Cautionary withdrawal (Mgal/d)	Cautionary withdrawal (percent of total)	Threatened withdrawal (Mgal/d)	Threatened withdrawal (percent of total)
Scenario 2–Expected growth (including USMC)						
Agafo Gumas	12	4.89	0	0	0	0
Andersen	10	0.79	0	0	0	0
Finegayan	12	6.16	1.88	31	0.71	12
Hagåtña	21	9.10	1.04	11	1.87	21
Mangilao	7	2.18	0	0	0	0
Yigo-Tumon	20	23.79	1.50	6	0	0
Total	**81**	**46.91**	**4.42**	**9**	**2.58**	**5**
Scenario 3–Expected growth (including redistributed USMC)						
Agafo Gumas	12	4.43	0	0	0	0
Andersen	10	1.04	0	0	0	0
Finegayan	12	5.56	1.59	29	0.41	7
Hagåtña	21	9.10	1.04	11	1.87	21
Mangilao	7	2.18	0	0	0	0
Yigo-Tumon	20	24.31	1.50	6	0	0
Total	**81**	**46.62**	**4.13**	**9**	**2.28**	**5**
Scenario 4–Expected growth (including redistributed USMC) with 5-year drought						
Agafo Gumas	12	4.43	2.45	55	0	0
Andersen	10	1.04	0	0	0	0
Finegayan	12	5.56	2.00	36	3.03	54
Hagåtña	21	9.10	2.25	25	4.02	44
Mangilao	7	2.18	0	0	0.45	21
Yigo-Tumon	20	24.31	12.90	53	4.59	19
Total	**81**	**46.62**	**19.61**	**42**	**12.09**	**26**
Scenario 5–Redistributed expected growth (including USMC)						
Agafo Gumas	12	4.43	0	0	0	0
Andersen	10	1.04	0	0	0	0
Finegayan	12	5.67	1.59	28	0	0
Hagåtña	21	8.87	2.27	26	0	0
Mangilao	7	2.18	0	0	0	0
Yigo-Tumon	20	24.31	1.27	5	0	0
Total	**81**	**46.51**	**5.13**	**11**	**0**	**0**

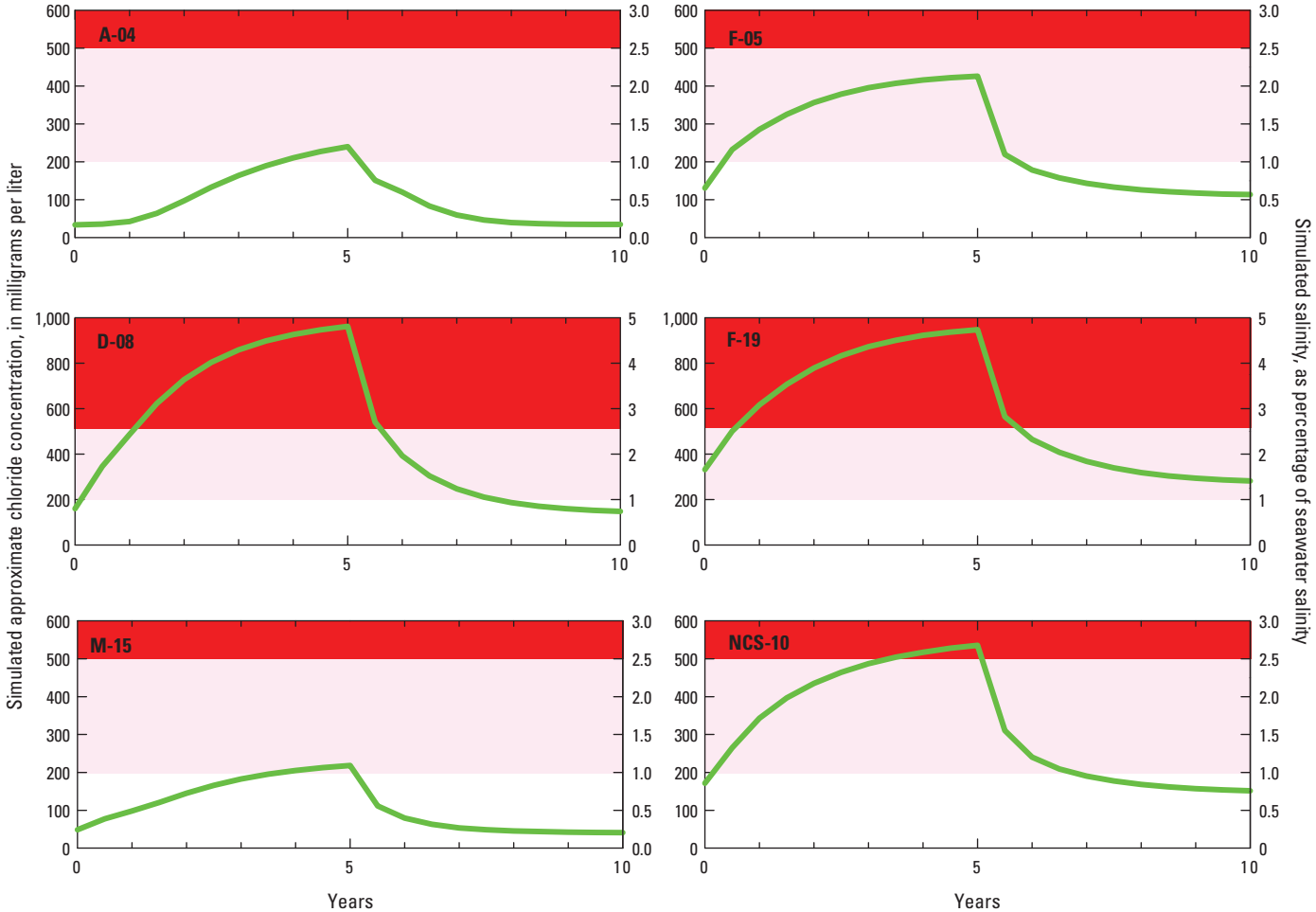


Figure 23. Simulated salinity data (green lines) for a hypothetical 5-year drought using 2010 pumping rates at selected wells in the Northern Guam Lens Aquifer, Guam. For each well shown, the simulated salinity is the average of the nodes representing the well. The pink area represents a cautionary salinity class, and the red area represents a threatened salinity class.

Drought Conditions With Reduced Withdrawal

To reduce the amount of water with salinity in the threatened class during a drought, withdrawal could be reduced to maintain salinity at all of the drinking-water wells below the threatened threshold (table 4). For this scenario, overall withdrawal in the NGLA is reduced by 20 percent to 32.18 Mgal/d to maintain all wells below the threatened threshold (table 5). This reduction results in 18.88 Mgal/d of cautionary yield (fig. 16*C*), about 59 percent of the withdrawal from the NGLA (table 5). The total water volume in the acceptable category is 13.3 Mgal/d. The Yigo-Tumon basin has the highest amount of cautionary yield (13.26 Mgal/d); this amount represents about 73 percent of the total water pumped from the basin. The Hagåtña basin has the second highest amount of cautionary yield (2.66 Mgal/d); this amount represents about 45 percent of the total water pumped from this basin.

Simulated Future Scenarios

The numerical model constructed for this study was used to quantify changes in groundwater level and salinity under various withdrawal and recharge scenarios (table 6). Recharge for all but the future drought scenario was based on average rainfall and 2004 land use. Future scenarios included groundwater withdrawal for average 2010–11 rates and locations plus additional pumping for planned growth of GWA and DoD needs (excluding USMC growth) (scenario 1), withdrawal at planned growth plus USMC growth (scenario 2), planned growth and USMC growth redistributed for lower salinity (scenario 3), redistributed USMC growth with a 5-year drought (scenario 4), and all growth redistributed to preclude withdrawals in the threatened class (scenario 5). All scenarios reached equilibrated hydrologic conditions for which no notable water-level or salinity changes were apparent after a few years. The simulated initial conditions for the average recharge scenarios were the final conditions from the

calibrated simulation. The initial conditions for the drought scenario were the final conditions for scenario 3.

Future planned growth scenarios were based on the most current average daily water-demand estimates available as provided by NAVFAC Pacific (written commun., 2013). Estimates were based on civilian and military population growth with and without the proposed USMC buildup. The baseline condition on which the growth demand was imposed was average 2010–11 rates (42.3 Mgal/d) and locations (table 6). The DoD water demand (excluding the USMC buildup) in 2028 was estimated to be 0.97 Mgal/d higher than current demand. The USMC buildup was preliminarily estimated to increase the water demand by an additional 1.79 Mgal/d. This is the estimate used in this study The final estimate for the USMC buildup was not available in time to incorporate into the scenarios described in this report, however the final demand is estimated to be less than 0.1 Mgal/d higher (NAVFAC Pacific, written commun., 2013), therefore the slight discrepancy won't make much difference to the final results. Furthermore, NAVFAC Pacific indicates that future estimates of average demand from the Air Force wells are expected to be lower than previously anticipated due to recent transmission system upgrades. The slightly higher demand used in this report will therefore produce results that may be slightly more conservative.

In the following scenarios, part of the estimated demand was met by adding seven new DoD wells, each withdrawing 0.256 Mgal/d (about 178 gallons per minute) on an annual basis, and the rest was met by increasing withdrawal at selected existing DoD wells. In practice, more than seven new wells may be needed to meet the average daily demand or any peak demands based on the local geology encountered when the wells are drilled. In general, spreading out the pumping to more wells could improve conditions by minimizing local saltwater upconing to individual wells. Water demand in 2028 for civilian population growth without the USMC buildup was estimated to be 3.47 Mgal/d higher than current demand. This figure includes 36 percent loss due to unaccounted-for water (including but not limited to conveyance losses). Additional civilian demands due to the USMC buildup were estimated to be 0.28 Mgal/d. Civilian demands were met by adding three new GWA wells and increasing withdrawal at selected existing GWA wells.

Table 6. Selected wells and withdrawal rates used in future scenarios, Northern Guam Lens Aquifer, Guam.

[Values in pink or red represent wells with salinity in the cautionary or threatened range, respectively; cautionary yield is the volume of withdrawn water that has a salinity roughly from 200 to 500 milligrams per liter of chloride; threatened yield is the volume of withdrawn water that has a salinity greater than roughly 500 milligrams per liter of chloride; well information and withdrawal rates provided by Guam Water Authority (GWA), Department of Defense (DoD), and Guam Environmental Protection Agency; modeled salinity is the average salinity from all of the nodes representing each pumped well]

Well name	Well owner	Withdrawal rate (million gallons per day)	Withdrawal rate change from average 2010–11 conditions (million gallons per day)				Withdrawal rate (million gallons per day)
		Average 2010–11	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Agafo Gumas basin							
AF-01	DoD	0.2048	0.097	0.097	0.097	0.097	0.3018
AF-02	DoD	0.1248	0.097	0.097	0.097	0.097	0.2218
AF-03	DoD	0.1864	0.097	0.097	0.097	0.097	0.2834
AF-04	DoD	0.1249	0.097	0.097	0.097	0.097	0.2219
AF-05	DoD	0.0813	0.097	0.097	0.097	0.097	0.1783
AG-01	GWA	0.0422	0	0	0	0	0.0422
AG-02	GWA	0.6615	0	0	0	0	0.6615
AG-10	GWA	0	0.400	0.400	0.400	0.400	0.4000
HGC-02	Private	0.7821	0	0	0	0	0.7821
HGC-03	Private	0.0983	0	0	0	0	0.0983
NCS-11	DoD	0.1973	0	0	–0.100	–0.100	0.0973
NCS-12	DoD	0.1891	0	0	–0.100	–0.100	0.0891
PW01	DoD	0	0	0.256	0	0	0
PW07	DoD	0	0	0.256	0.256	0.256	0.2560
PW11	DoD	0	0	0.256	0.256	0.256	0.2560
PW14	DoD	0	0	0.256	0.256	0.256	0.2560
PW16	DoD	0	0	0.256	0.256	0.256	0.2560
PW18	DoD	0	0	0.256	0.256	0.256	0.2560
PW28	DoD	0	0	0.256	0.256	0.256	0.2560
Site 12	GWA	0	0.400	0.400	0.400	0.400	0.4000
Total		**2.6927**	**1.285**	**3.077**	**2.621**	**2.621**	**5.3140**
Andersen basin							
BPM	DoD	0.0542	0	0	0	0	0.0542
Y-15	GWA	0.7878	0	0	0	0	0.7878
PW57	DoD	0	0	0	0.256	0.256	0.2560
Total		**0.8420**	**0**	**0**	**0.256**	**0.256**	**1.0980**
Finegayan basin							
D-24	GWA	0.2653	0	0	0	**0**	0.2653
F-01	GWA	0.1482	0	0	0	**0**	0.1300
F-02	GWA	0.2045	0	0	0	**0**	0.2045
F-03	GWA	0.2220	0	0	0	**0**	0.2220
F-04	GWA	0.2142	0	0	0	**0**	0.2142
F-05	GWA	0.2696	0	0	0	0	0.2696
F-06	GWA	0.3050	**0**	**0**	**–0.200**	**–0.200**	**0**

Table 6. Selected wells and withdrawal rates used in future scenarios, Northern Guam Lens Aquifer, Guam.—Continued

[Values in pink or red represent wells with salinity in the cautionary or threatened range, respectively; cautionary yield is the volume of withdrawn water that has a salinity roughly from 200 to 500 milligrams per liter of chloride; threatened yield is the volume of withdrawn water that has a salinity greater than roughly 500 milligrams per liter of chloride; well information and withdrawal rates provided by Guam Water Authority (GWA), Department of Defense (DoD), and Guam Environmental Protection Agency; modeled salinity is the average salinity from all of the nodes representing each pumped well]

Well name	Well owner	Withdrawal rate (million gallons per day)	Withdrawal rate change from average 2010–11 conditions (million gallons per day)				Withdrawal rate (million gallons per day)
		Average 2010–11	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
F-07	GWA	0.2826	0	0	0	0	0.2826
F-08	GWA	0.2161	0	0	0	0	0.2460
F-09	GWA	0.1824	0	0	0	0	0.1824
F-10	GWA	0.2661	0	0	0	0	0.2661
F-11	GWA	0.2493	0	0	0	0	0.2493
F-12	GWA	0.2803	0	0	0	0	0.3600
F-13	GWA	0.3138	0	0	0	0	0.3138
F-15	GWA	0.3121	0	0	0	0	0.3121
F-16	GWA	0.3836	0	0	0	0	0.3836
F-17	GWA	0.3034	0	0	0	0	0.3294
F-19	GWA	0.2233	0	0	0	0	0.2233
F-20	GWA	0.2236	0	0	–0.100	–0.100	0.1236
H-01	GWA	0.4045	0	0	–0.100	–0.100	0.1979
NCS-06	DoD	0.1918	0	0	–0.100	–0.100	0.1918
NCS-07	DoD	0.1930	0	0	0	0	0.1930
NCS-09	DoD	0.2671	0	0	0	0	0.2671
NCS-10	DoD	0.1881	0	0	–0.100	–0.100	0.1881
NCS-A	DoD	0	0	0	0	0	0
NCS-B	DoD	0.0524	0	0	0	0	0.0520
Total		**6.1624**	**0**	**0**	**–0.600**	**–0.600**	**5.6678**
Hagåtña basin							
A-01	GWA	0.2894	0	0	0	0	0.3890
A-02	GWA	0.2725	0	0	0	0	0.3830
A-03	GWA	0.2642	0	0	0	0	0.3540
A-04	GWA	0.4391	0	0	0	0	0.4391
A-05	GWA	0.3796	0	0	0	0	0.4200
A-06	GWA	0.4141	0	0	0	0	0.4141
A-08	GWA	0.3862	0	0	0	0	0.3862
A-09	GWA	0.3425	0	0	0	0	0.3425
A-10	GWA	0.3940	0	0	0	0	0.3152
A-12	GWA	0.1169	0	0	0	0	0.2170
A-13	GWA	0.4533	0	0	0	0	0.3400
A-14	GWA	0.2320	0	0	0	0	0.3040
A-15	GWA	0.4317	0	0	0	0	0.4317
A-17	GWA	0.3552	0	0	0	0	0.2664
A-18	GWA	0.2940	0	0	0	0	0.2940
A-19	GWA	0.2291	0	0	0	0	0.2291

Table 6. Selected wells and withdrawal rates used in future scenarios, Northern Guam Lens Aquifer, Guam.—Continued

[Values in pink or red represent wells with salinity in the cautionary or threatened range, respectively; cautionary yield is the volume of withdrawn water that has a salinity roughly from 200 to 500 milligrams per liter of chloride; threatened yield is the volume of withdrawn water that has a salinity greater than roughly 500 milligrams per liter of chloride; well information and withdrawal rates provided by Guam Water Authority (GWA), Department of Defense (DoD), and Guam Environmental Protection Agency; modeled salinity is the average salinity from all of the nodes representing each pumped well]

Well name	Well owner	Withdrawal rate (million gallons per day)	Withdrawal rate change from average 2010–11 conditions (million gallons per day)				Withdrawal rate (million gallons per day)
		Average 2010–11	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
A-21	GWA	0.4059	0	0	0	0	0.4059
A-23	GWA	0.4656	0	0	0	0	0.4656
A-25	GWA	0.4830	0	0	0	0	0.4830
A-26	GWA	0.0684	0	0	0	0	0.1680
A-30	GWA	0.9436	0	0	0	0	0.9436
A-31	GWA	0.4056	0	0	0	0	0.4056
A-32	GWA	0.3286	0	0	0	0	0.1000
FFH-01–08	Private	0.4365	0	0	0	0	0.4365
HRP-01	Private	0.0951	0	0	0	0	0.0951
HRP-02	Private	0.0783	0	0	0	0	0.0783
NAS-01	GWA	0.3727	0	0	0	0	0.3727
NRMC-01	DoD	0.1795	0	0	0	0	0
NRMC-02	DoD	0.1560	0	0	0	0	0
NRMC-03	DoD	0.0001	0	0	0	0	0
Total		**9.7126**	**0**	**0**	**0**	**0**	**9.4795**
Mangilao basin							
EX-11	GWA	0.3376	0	0	0	0	0.3376
M-01	GWA	0.2060	0	0	0	0	0.2060
M-02	GWA	0.2566	0	0	0	0	0.2566
M-03	GWA	0.3527	0	0	0	0	0.3527
M-04	GWA	0.3482	0	0	0	0	0.3482
M-08	GWA	0.2234	0	0	0	0	0.2234
M-09	GWA	0.0976	0	0	0	0	0.0976
M-23	GWA	0.3605	0	0	0	0	0.3605
MGC-04	Private	0.0001	0	0	0	0	0.0001
Total		**2.1826**	**0**	**0**	**0**	**0**	**2.1826**
Yigo-Tumon basin							
D-01	GWA	0.3189	0	0	0	0	0.3189
D-02	GWA	0.2897	0	0	0	0	0.2897
D-04	GWA	0.3573	0	0	0	0	0.3573
D-05	GWA	0.2456	0	0	0	0	0.2456
D-06	GWA	0.3473	0	0	0	0	0.3473
D-07	GWA	0.2967	0	0	0	0	0.2967
D-08	GWA	0.2298	0	0	0	0	0.2298
D-09	GWA	0.2960	0	0	0	0	0.2960
D-10	GWA	0.3478	0.052	0.052	0.052	0.052	0.3998
D-11	GWA	0.2092	0.100	0.100	0.100	0.100	0.3092

Table 6. Selected wells and withdrawal rates used in future scenarios, Northern Guam Lens Aquifer, Guam.—Continued

[Values in pink or red represent wells with salinity in the cautionary or threatened range, respectively; cautionary yield is the volume of withdrawn water that has a salinity roughly from 200 to 500 milligrams per liter of chloride; threatened yield is the volume of withdrawn water that has a salinity greater than roughly 500 milligrams per liter of chloride; well information and withdrawal rates provided by Guam Water Authority (GWA), Department of Defense (DoD), and Guam Environmental Protection Agency; modeled salinity is the average salinity from all of the nodes representing each pumped well]

Well name	Well owner	Withdrawal rate (million gallons per day)	Withdrawal rate change from average 2010–11 conditions (million gallons per day)				Withdrawal rate (million gallons per day)
		Average 2010–11	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
D-12	GWA	0.2783	0	0	0	0	0.2783
D-13	GWA	0	0	0	0	0	0
D-14	GWA	0.3591	0	0	0	0	0.3591
D-15	GWA	0.3279	0	0	0	0	0.3279
D-16	GWA	0.3008	0	0	0	0	0.3008
D-19	GWA	0.2665	0	0	0	0	0.2665
D-20	GWA	0.3069	0	0	0	0	0.3069
D-21	GWA	0.3093	0	0	0	0	0.3093
D-25	GWA	0.4490	0	0	0	0	0.4490
D-26	GWA	0.4301	0	0	0	0	0.4301
D-27	GWA	0.5568	0	0	0	0	0.5568
D-28	GWA	0.2580	0	0	0	0	0.2580
EX-05A	GWA	0.5479	0	0	0	0	0.5479
FM-01	Private	0.0515	0	0	0	0	0.0515
GH-501	GWA	0.3112	0	0	0	0	0.3112
GPH	Private	0.0220	0	0	0	0	0.0220
M-05	GWA	0.3092	0	0	0	0	0.3092
M-06	GWA	0.2322	0	0	0	0	0.2322
M-07	GWA	0.3080	0.100	0.100	0.100	0.100	0.4080
M-12	GWA	0.0584	0	0	0	0	0.0584
M-15	GWA	0.3036	0.120	0.120	0.120	0.120	0.4236
M-17B	GWA	0.4379	0	0	0	0	0.4379
M-18	GWA	0.3279	0	0	0	0	0.3279
M-20A	GWA	0.3947	0	0	0	0	0.3947
M-21	GWA	0.4633	0	0	0	0	0.4633
MW-01	DoD	0.0939	0	0	0	0	0.0939
MW-03	DoD	0.0469	0	0	0	0	0.0469
MW-05	DoD	0.0996	0.097	0.097	0.097	0.097	0.1966
MW-06	DoD	0.4611	0.097	0.097	0.097	0.097	0.5581
MW-07	DoD	0.2274	0.097	0.097	0.097	0.097	0.3244
MW-08	DoD	0.5308	0.097	0.097	0.097	0.097	0.6278
MW-09	DoD	0.3718	0.097	0.097	0.097	0.097	0.4688
PBI-01	Private	0.0113	0	0	0	0	0.0113
PIC	Private	0.2563	0	0	0	0	0.2563
Site 08	GWA	0	0.400	0.400	0.400	0.400	0.4000
Tumon	DoD	0	0	0.280	0.800	0.800	0.8000
Y-01	GWA	0.2928	0.160	0.160	0.160	0.160	0.4528
Y-02	GWA	0.2326	0.230	0.230	0.230	0.230	0.4626

Table 6. Selected wells and withdrawal rates used in future scenarios, Northern Guam Lens Aquifer, Guam.—Continued

[Values in pink or **red** represent wells with salinity in the cautionary or **threatened** range, respectively; cautionary yield is the volume of withdrawn water that has a salinity roughly from 200 to 500 milligrams per liter of chloride; **threatened yield** is the volume of withdrawn water that has a salinity greater than roughly 500 milligrams per liter of chloride; well information and withdrawal rates provided by Guam Water Authority (GWA), Department of Defense (DoD), and Guam Environmental Protection Agency; modeled salinity is the average salinity from all of the nodes representing each pumped well]

Well name	Well owner	Withdrawal rate (million gallons per day)	Withdrawal rate change from average 2010–11 conditions (million gallons per day)				Withdrawal rate (million gallons per day)
		Average 2010–11	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Y-03	GWA	0.2910	0.160	0.160	0.160	0.160	0.4510
Y-04	GWA	0.2930	0.050	0.050	0.050	0.050	0.3430
Y-05	GWA	0.2877	0.100	0.100	0.100	**0.100**	0.3877
Y-06	GWA	0.3522	0.040	0.040	0.040	0.040	0.3922
Y-07	GWA	0.5416	0	0	0	0	0.5416
Y-09	GWA	0.2717	0.250	0.250	0.250	0.250	0.5217
Y-10	GWA	0.4454	0	0	0	0	0.4454
Y-12	GWA	0.4966	0	0	0	0	0.4966
Y-14	GWA	0.4966	0	0	0	0	0.4966
Y-16	GWA	0.4499	0	0	0	0	0.4499
Y-17	GWA	0.4657	0	0	0	0	0.4657
Y-18	GWA	0.4280	0.160	0.160	0.160	0.160	0.5880
Y-19	GWA	0.7535	0.120	0.120	0.120	**0.120**	0.8735
Y-20	GWA	0.9079	0	0	0	**0**	0.9079
Y-21	GWA	0.2612	0.140	0.140	0.140	0.140	0.4012
Y-22	GWA	0.3752	0.100	0.100	0.100	0.100	0.4752
Y-23	GWA	0.4105	0.388	0.388	0.388	0.388	0.7985
Total		**20.7009**	**3.155**	**3.435**	**3.955**	**3.955**	**24.6559**

Scenario 1—2010–11 Withdrawal Rates and Locations Plus Expected GWA and DoD (Excluding USMC) Growth With Average Recharge

In scenario 1, average recharge, the most recent withdrawals, and civilian and military growth estimates (excluding the USMC buildup) were used to simulate the effects of continuing growth on the freshwater lens. Assigned total recharge over the model domain was 225 Mgal/d, based on 2004 land use and average rainfall (table 3). Total withdrawal was simulated by using average annual reported 2010–11 withdrawal plus GWA and DoD growth (table 6). Total withdrawal averaged 46.76 Mgal/d throughout the NGLA; non-drinking-water wells account for 1.89 Mgal/d of this total. GWA growth was accommodated by adding three new wells (AG10, site 12, and site 08) withdrawing 0.4 Mgal/d each at locations provided by GWA (Brett Railey, GWA, written commun., November 18, 2012) (fig. 24*A*). The remaining 2.27 Mgal/d of expected demand from the GWA wells was added by increasing withdrawal at 16 GWA wells in the Yigo-Tumon area. DoD growth was accommodated by increasing withdrawal by 0.097 Mgal/d at each of 10 existing wells (AF-01 to 05; MW-05 to 09).

Because withdrawal increased, the freshwater body became thinner and the simulated salinity in two more of the wells degraded to the cautionary (well D-08) or threatened (well H-01) salinity class (fig. 25*A*). In general, wells that are completed deeper or closer to the coast and downgradient of areas of increased withdrawal are more vulnerable to increased salinities (fig. 26*A*). Overall, 28 wells had chloride concentration increases greater than 10 mg/L compared to 2010 conditions. At well A-15, the withdrawal rate for scenario 1 is lower than that used during the 2010 average conditions, and the well classification moved from the cautionary (table 4) to the normal category (table 6).

For scenario 1, withdrawal of 44.85 Mgal/d of drinking water from the NGLA results in 3.72 Mgal/d of cautionary yield and 2.58 Mgal/d of threatened yield (table 5). The Hagåtña basin has the highest amount of combined cautionary (1.04 Mgal/d) and threatened (1.87 Mgal/d) yield; this amount represents about 32 percent of the total water pumped from the Hagåtña basin.

Scenario 2—2010–11 Withdrawal Rates and Locations Plus Expected GWA and DoD (Including USMC) Growth With Average Recharge

In scenario 2, average recharge, average annual reported 2010–11 withdrawal, and civilian and military growth estimates (including the USMC buildup) were used to simulate the effects of continued growth on the freshwater lens (table 6). Assigned total recharge over the model domain was the same as in scenario 1 (225 Mgal/d) (table 3). Total withdrawal averaged 48.81 Mgal/d throughout the NGLA; non-drinking-water wells account for 1.89 Mgal/d of this total. GWA and DoD non-USMC growth was accommodated the same way as in scenario 1. Growth for the USMC buildup was accommodated by adding 0.28 Mgal/d for GWA needs at the Tumon well and 1.79 Mgal/d at seven new wells in the Agafo Gumas basin (fig. 24*B*). The new well locations were obtained from proposed well locations presented in "*Guam Water Well Testing Study to Support U.S. Marine Corps Relocation to Guam"* (AECOM Technical Services, Inc., 2011), and the well numbers used in this study (designated with PWxx; xx is a two-digit number) match those presented in table 7-1 of that report.

For this scenario, withdrawal has increased about 2.1 Mgal/d relative to scenario 1, mostly in the Agafo Gumas basin; therefore, most of the significant salinity increases in pumped wells are in this basin and the adjacent downgradient Finegayan basin (figs. 25*B*). The simulated salinity in 3 of the wells (F-02, F-13, and NCS-10) moves into the cautionary salinity class (table 6), and 17 wells show salinity increases equal to or greater than 10 mg/L chloride concentration (fig. 26*B*).

Overall, withdrawal of 46.92 Mgal/d of drinking water from the NGLA results in 4.42 Mgal/d of cautionary yield and 2.58 Mgal/d of threatened yield (table 5). The Hagåtña basin has the highest amount of combined cautionary (1.04 Mgal/d) and threatened (1.87 Mgal/d) yield; this amount represents about 32 percent of the total water pumped from the Hagåtña basin. The Finegayan basin has the second highest amount of combined cautionary (1.88 Mgal/d) and threatened (0.71 Mgal/d) yield; this amount represents about 42 percent of the total water pumped from this basin.

Scenario 3—2010–11 Withdrawal Rates and Locations Plus Planned and USMC Growth (Redistributed) With Average Recharge

In scenario 3, the pumping distribution from scenario 2 was redistributed to reduce salinity in some of the wells (table 6). Assigned total recharge was the same as for scenario 2 (table 3) and total withdrawal was reduced to 48.53 Mgal/d. Growth for the USMC buildup was accommodated by adding 0.8 Mgal/d for GWA and DoD needs at the Tumon well and 1.79 Mgal/d at seven new wells (designated with PWxx) in the Agafo Gumas and Andersen basins (fig. 24*C*). The Tumon well is expected to provide 0.8 Mgal/d of water; however, at the time of this study, final plans for the distribution of this water to the DoD and GWA systems are not completed. Therefore, for the purposes of scenario 3, the changes in water distribution were split equally between each user. The addition of water from the Tumon well was balanced by lowering the withdrawals at DoD wells NCS-06,-10, -11, and -12 (0.1 Mgal/d each) and at GWA wells F-06 (0.2 Mgal/d) and F-20 and H-01 (0.1 Mgal/d each). Withdrawal at proposed well PW01 was replaced by the same amount from PW57 in the Andersen basin because PW01 salinity in scenario 2 was very close to the cautionary category.

Overall, withdrawal of 46.62 Mgal/d of drinking water from the NGLA results in 4.13 Mgal/d of cautionary yield and 2.28 Mgal/d of threatened yield (table 5, fig. 25*C*), a decrease of about 0.54 Mgal/d of cautionary and threatened yield as compared to scenario 2. Thirteen wells had chloride concentration increases greater than 10 mg/L relative to 2010 conditions, four fewer wells than in scenario 2 (fig. 26*C*). The Hagåtña basin has the highest amount of combined cautionary (1.04 Mgal/d) and threatened (1.87 Mgal/d) yield; this amount represents about 32 percent of the total water pumped from the Hagåtña basin. The Finegayan basin has the second highest amount of combined cautionary (1.59 Mgal/d) and threatened (0.41 Mgal/d) yield; this amount represents about 36 percent of the total water pumped from this basin.

Scenario 4—2010–11 Withdrawal Rates and Locations Plus Planned and USMC Growth (Redistributed) With 5-Year Drought

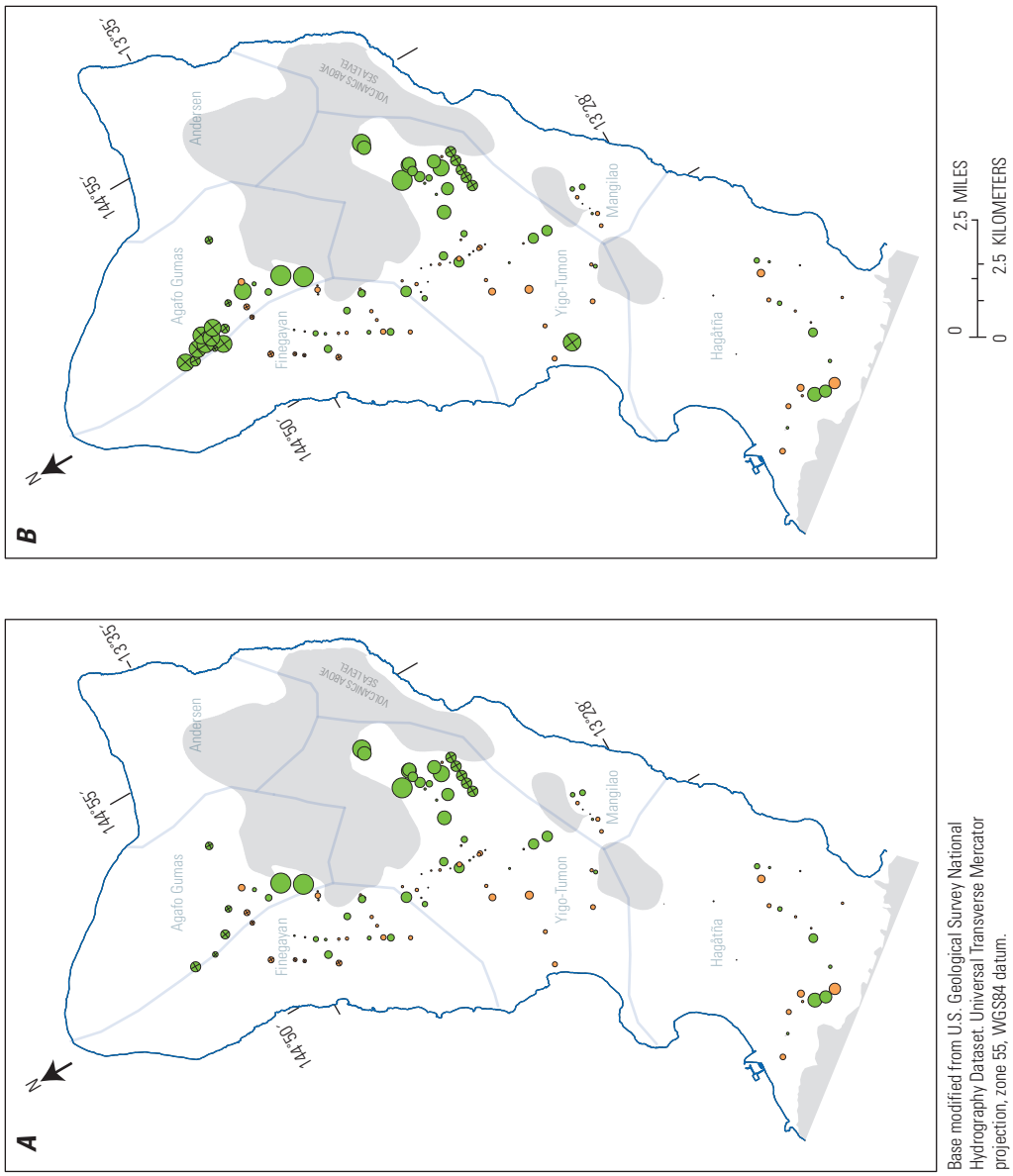
The effects of a 5-year drought on the pumping distribution including the USMC buildup were investigated in scenario 4. Assigned total recharge over the model domain was 155 Mgal/d, based on 2004 land use and a 5-year drought using recharge conditions estimated with 1969–73 rainfall (table 3). The period 1969–73 had the lowest recorded rainfall (and therefore lowest average recharge) for any 5-year period on Guam (Johnson, 2012). Withdrawal rates were the same as for scenario 3 for all wells (table 6, fig. 24*C*). This scenario represents generalized conditions, because the decrease in recharge during the 5-year drought is imposed immediately and constantly over the 5-year period, and the results are presented at the end of 5 years of pumping at the same rates throughout the drought to meet all demands.

Overall, withdrawal of 46.62 Mgal/d of drinking water from the NGLA after 5 years of the drought results in 19.61 Mgal/d of cautionary yield and 12.09 Mgal/d of threatened yield (table 5), a total of about 68 percent of the entire withdrawal from the NGLA (fig. 27*A*). The Hagåtña basin has the highest amount of combined cautionary (2.25 Mgal/d) and threatened (4.02 Mgal/d) yield; this amount represents about 69 percent of the total water pumped from the Hagåtña basin. The Finegayan basin has the second highest amount of combined cautionary (2.0 Mgal/d) and threatened (3.03 Mgal/d) yield; this amount represents about 90 percent of the total water pumped from this basin.

Scenario 5—Redistributed 2010–11, Planned, and USMC Withdrawal Rates and Locations With Average Recharge

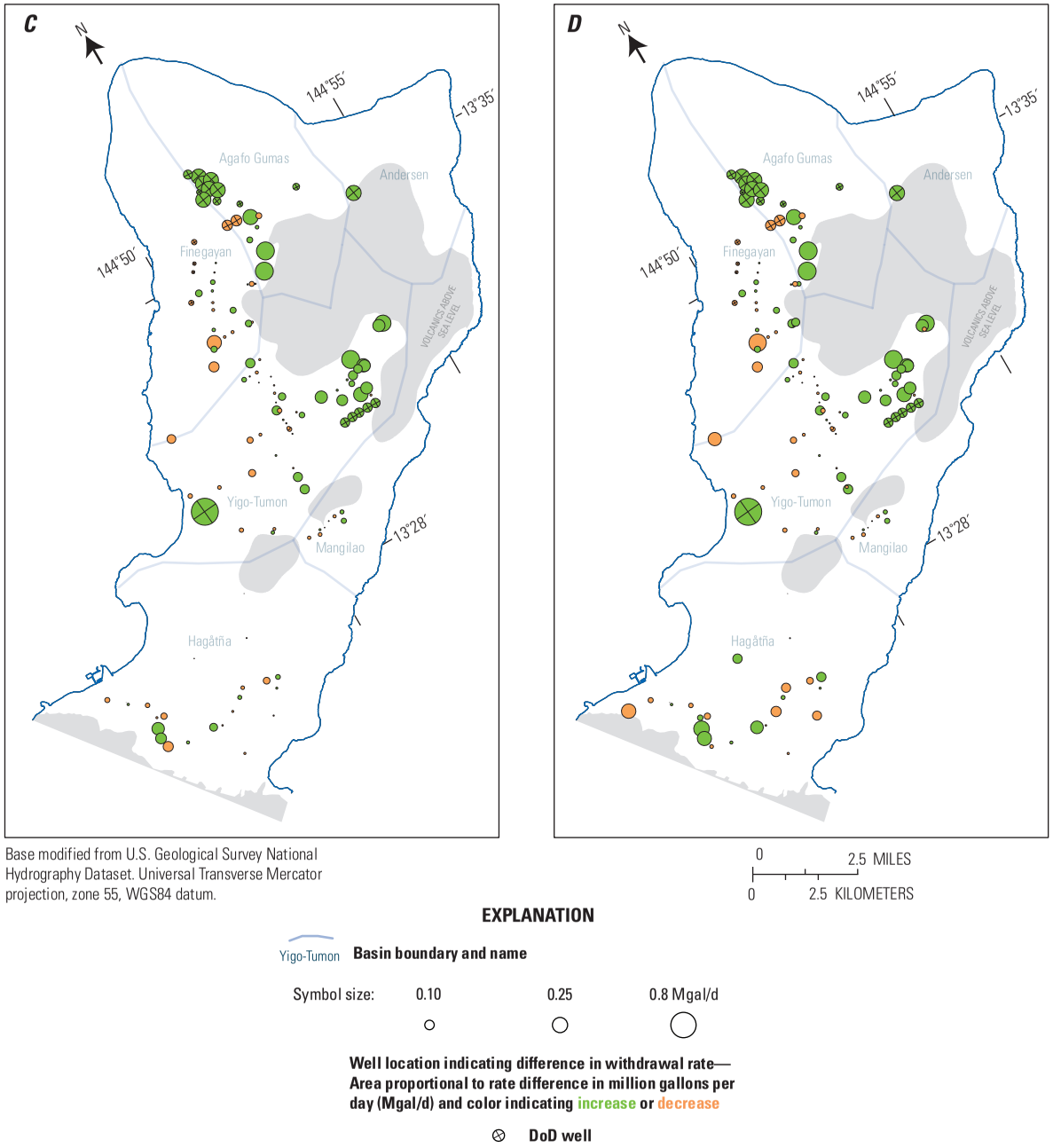
In scenario 5, the pumping distribution was changed to lower salinity in all of the DoD and GWA wells below the threatened threshold (table 6). Assigned total recharge was the same as for scenario 3 (table 2) and total withdrawal averaged 46.51 Mgal/d. As in scenarios 3 and 4, growth for the USMC buildup was accommodated by adding 0.8 Mgal/d for GWA and DoD needs at the Tumon well and 1.79 Mgal/d at seven new wells in the Agafo Gumas and Andersen basins (fig. 24*D*). In the Finegayan basin, withdrawal was reduced by about 0.5 Mgal/d relative to 2010 rates, and this reduction includes eliminating withdrawal at well F-06. In the Hagåtña basin, withdrawal was reduced by about 0.2 Mgal/d, and this includes eliminating withdrawal at wells NRMC-01, 02, and -03. Withdrawal in the Yigo-Tumon basin increased about 3.96 Mgal/d relative to 2010 rates. Withdrawal in the Agafo Gumas, Andersen, and Mangilao basins remained unchanged for this scenario.

Overall, withdrawal of 46.51 Mgal/d of drinking water from the NGLA with the redistributed pumping locations and rates results in only 5.13 Mgal/d of cautionary yield (table 5) or about 11 percent of the entire withdrawal from the NGLA (fig. 27*B*). The Hagåtña basin has the highest amount of combined cautionary yield (2.27 Mgal/d) or about 28 percent of the total water pumped from the Hagåtña basin. The Finegayan basin has the second highest amount of cautionary (1.59 Mgal/d) yield; this amount represents about 26 percent of the total water pumped from this basin.



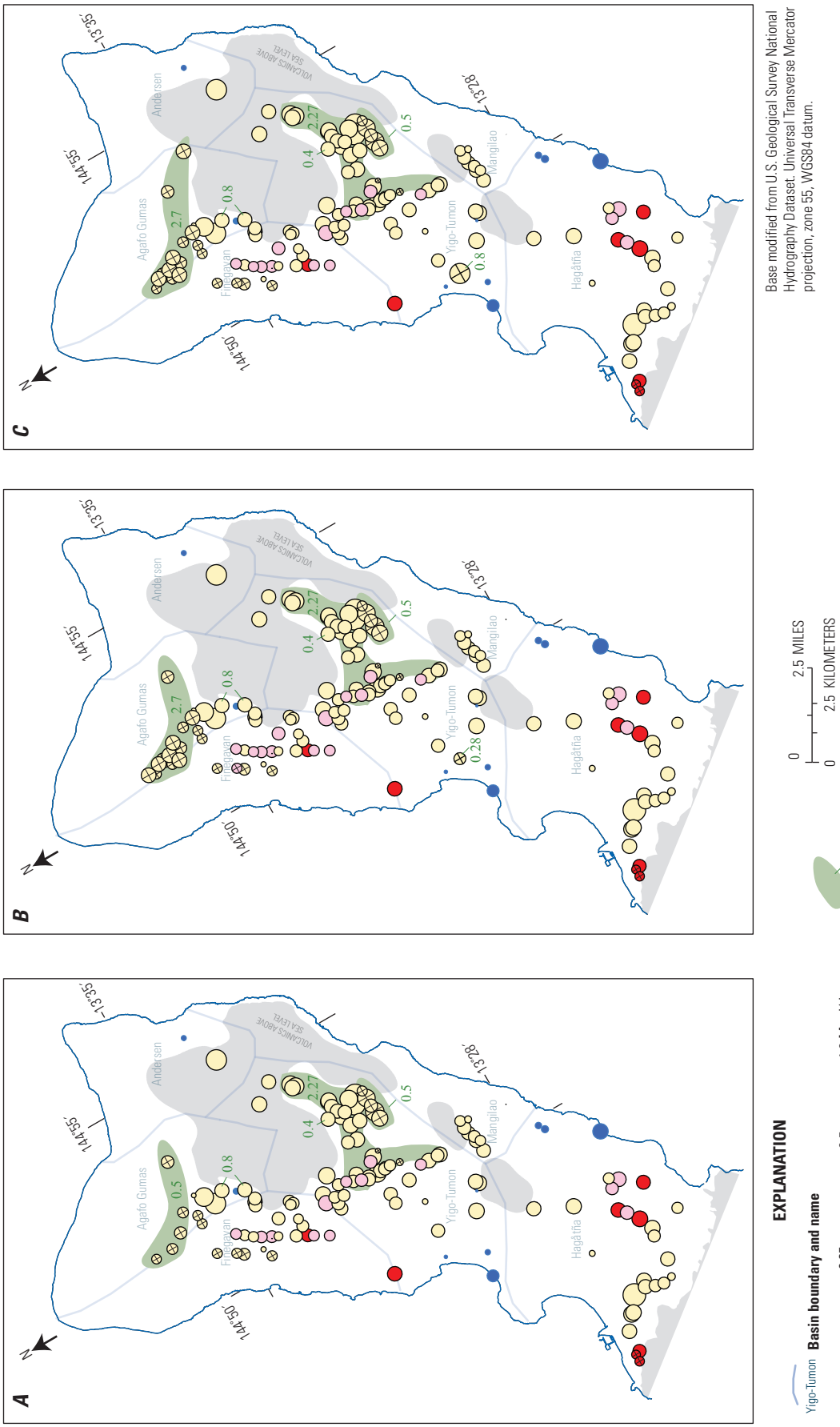
Base modified from U.S. Geological Survey National Hydrography Dataset. Universal Transverse Mercator projection, zone 55, WGS84 datum.

Figure 24. Difference in withdrawal at pumped wells relative to 2010 pumping rates in the Northern Guam Lens Aquifer, Guam. *A*, Scenario 1. *B*, Scenario 2. *C*, Scenarios 3 and 4. *D*, Scenario 5.



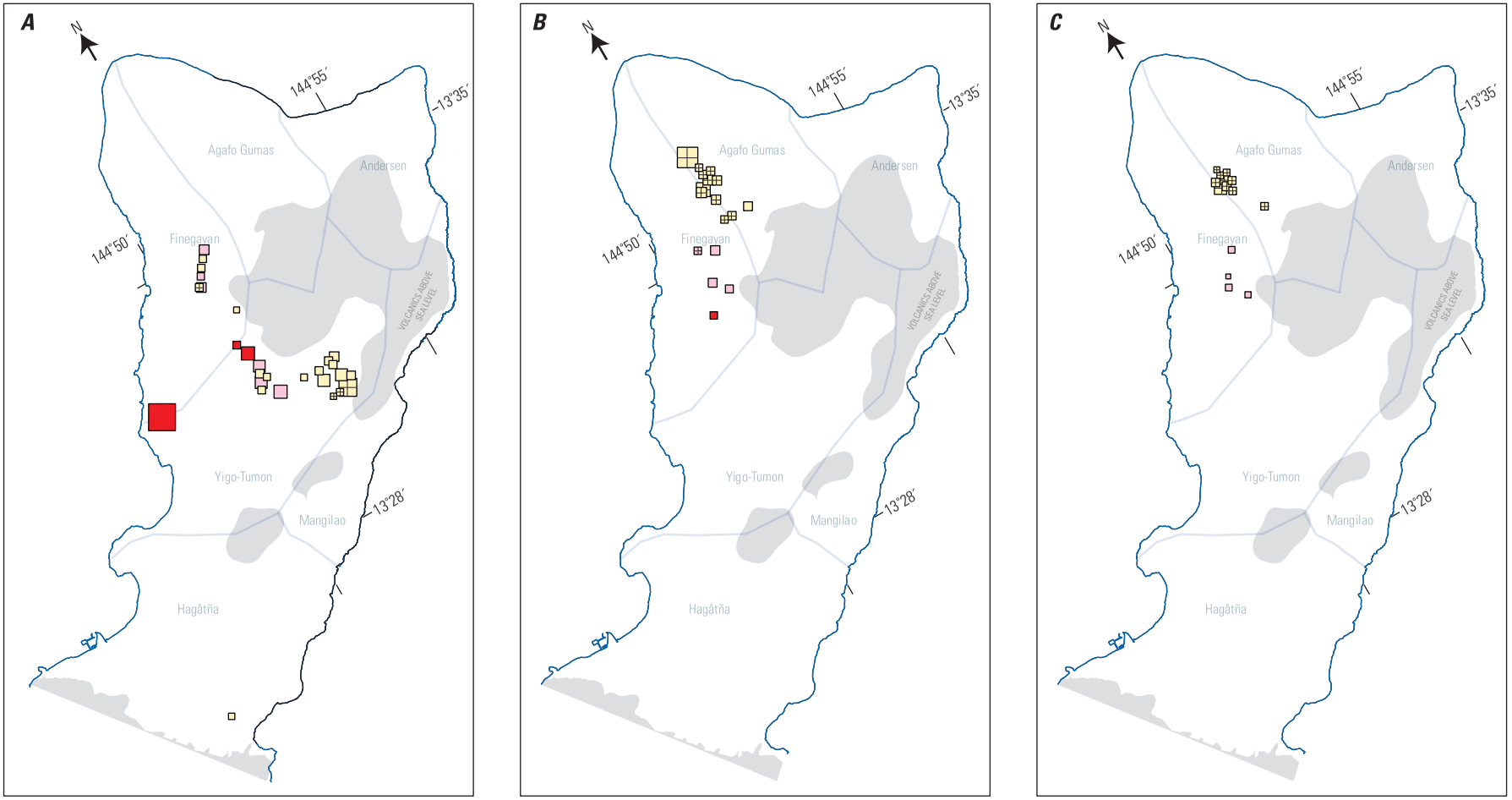
Base modified from U.S. Geological Survey National Hydrography Dataset. Universal Transverse Mercator projection, zone 55, WGS84 datum.

Figure 24. Difference in withdrawal at pumped wells relative to 2010 pumping rates in the Northern Guam Lens Aquifer, Guam. *A*, Scenario 1. *B*, Scenario 2. *C*, Scenarios 3 and 4. *D*, Scenario 5.—Continued



Base modified from U.S. Geological Survey National Hydrography Dataset. Universal Transverse Mercator projection, zone 55, WGS84 datum.

Figure 25. Simulated salinity at pumped wells in the Northern Guam Lens Aquifer, Guam. *A*, Scenario 1. *B*, Scenario 2. *C*, Scenario 3.



EXPLANATION

Yigo-Tumon **Basin boundary and name**

Symbol size: 25 mg/L 50 mg/L 100 mg/L

Symbol color: Acceptable Cautionary Threatened

Well location indicating salinity change and modeled salinity—Area proportional to chloride change and color indicating final chloride concentration in milligrams per liter (mg/L); pink (200 to 500 mg/L) is cautionary and red (> 500 mg/L) is threatened

DoD well

SCALE

0 2.5 MILES

0 2.5 KILOMETERS

Base modified from U.S. Geological Survey National Hydrography Dataset. Universal Transverse Mercator projection, zone 55, WGS84 datum.

Figure 26. Simulated salinity difference at pumped drinking-water wells in the Northern Guam Lens Aquifer, Guam. *A*, Between 2010 conditions and scenario 1. *B*, Between scenarios 2 and 1. *C*, Between scenarios 3 and 1.

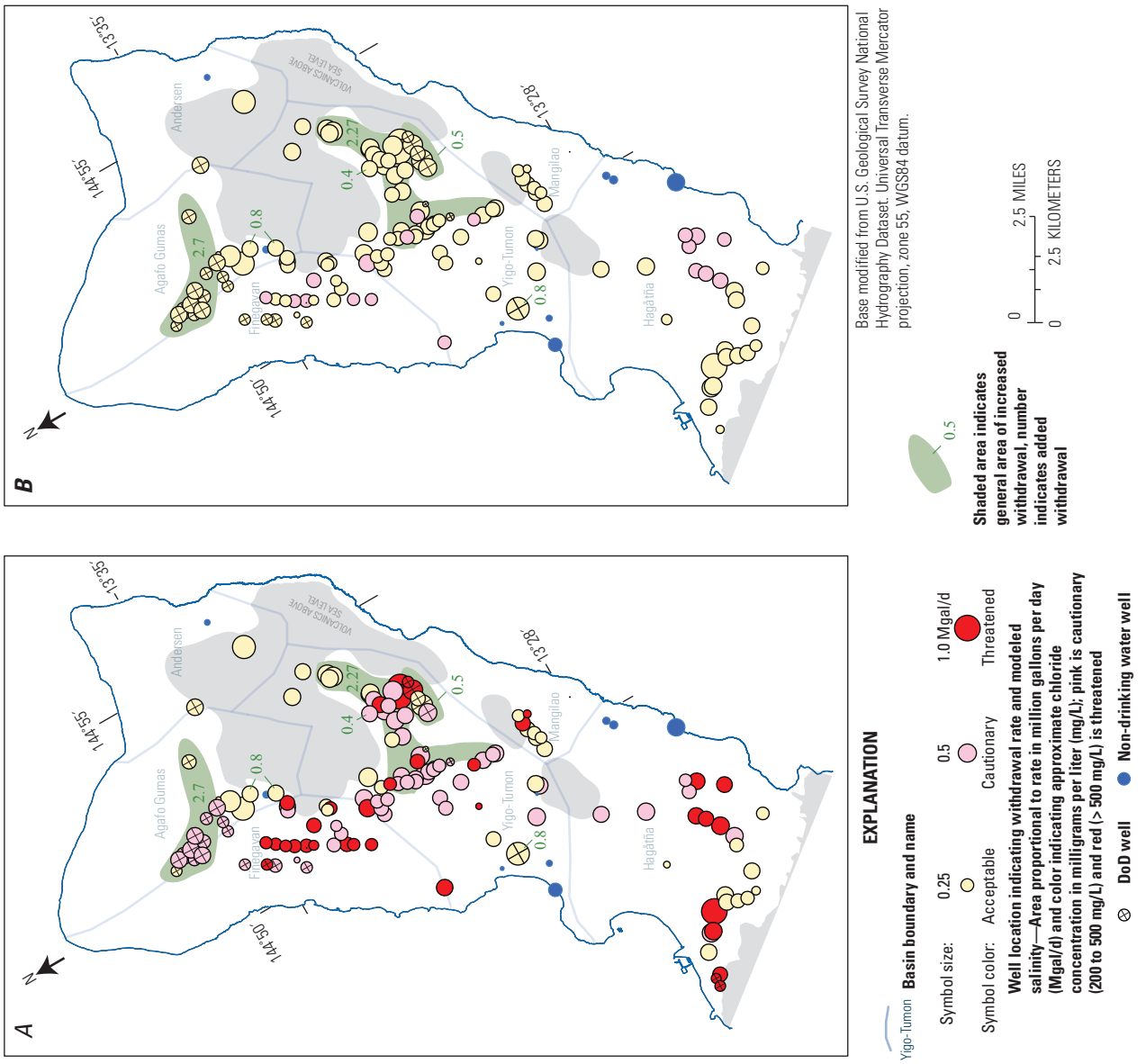


Figure 27. Simulated salinity at pumped wells in the Northern Guam Lens Aquifer, Guam. *A*, Scenario 4. *B*, Scenario 5.

Model Sensitivity to Parameter Variability

The distributions of parameter values assigned in the model were kept simple to avoid creating an overly complex model that could not be justified on the basis of existing information. Localized heterogeneity and anisotropy in the groundwater system likely exists but is poorly understood where hydrologic data are lacking. Values assigned to model parameters initially were based on existing estimates from previous field and modeling studies and subsequently adjusted to match historical water-level and salinity observations. The numerical model is well constrained because it had to match average water-level and tidal (amplitude and lags) observations as presented in Rotzoll and others (2013) and then, with further fine-tuning, the model matched salinity profiles with depth and chloride concentrations at pumped wells, as presented in this report. This required an extensive trial and error process in which the sensitivity of water levels and salinity to the various model parameters was evaluated until the best parameter combination was determined.

Through the calibration process, several hydrologic properties stood out as being the most sensitive to producing the desired match to observed conditions. With the exception of the areas containing the Argillaceous Limestone, simulated water levels throughout most of the NGLA are sensitive to the horizontal hydraulic conductivity where the water level was measured and to the aquifer hydraulic conductivity along the entire flow path between the observation well and the coastal discharge location. For example, water levels in the Yigo-Tumon basin are sensitive to the horizontal hydraulic conductivity of the Barrigada Limestone in the island's interior and to the horizontal hydraulic conductivity of the Mariana Limestone along the western coast, including the area of high hydraulic conductivity near Haputo Bay where a significant part of the groundwater flow through this basin discharges (fig. 19). However, Yigo-Tumon basin water levels are not sensitive to the hydraulic conductivity of the Mariana Limestone along the northern or eastern coasts or to the Argillaceous Limestone underlying much of the Hagåtña Basin. Water levels in the Argillaceous Limestone are mainly sensitive to the horizontal hydraulic conductivity of that zone and not sensitive to the coastal zone of Mariana Limestone anywhere around the island's perimeter. Slightly different combinations of horizontal hydraulic conductivity for the Barrigada and Mariana Limestone can produce simulated water levels that match measured water levels nearly as well as the final values presented in table 2; however, changes in horizontal hydraulic conductivity greater than about 20 percent of these values are sufficient to make the match unacceptable.

Simulated salinity profiles and salinities from pumped wells are most sensitive to the transverse dispersivity values used in all rock types. Because dispersion coefficients from field observations are poorly known, this parameter is usually modified in the model to produce the best fit with measured salinity profiles. In general, dispersivity values were kept as low as possible to match the sharp transition zone observed in most of the deep observation wells without producing unacceptable levels of numerical dispersion in the model results. As transverse dispersivity values are increased 100 percent or greater, the simulated transition zone shown in the salinity profiles becomes increasingly smeared out and less representative of observed conditions.

The chloride-concentration changes during the drought simulations are most sensitive to the effective-porosity values. Higher effective-porosity values produce slower changes in chloride concentration over time because flow in the hydrologic system is slowed. Therefore, the effects of drought after 5 years would be less pronounced (lower salinity in pumped wells) for effective-porosity values higher than the final values presented in table 2.

Study and Model Limitations

The numerical model developed for this study simulates water levels and salinity on a regional scale and may not accurately predict either the pumped water level at an individual well or the salinity of water pumped from that well. Salinity of water pumped from a well may be controlled by local heterogeneities in the aquifer that are not represented in the model, and the level of model discretization affects the numerical accuracy with which transport mechanisms are simulated. The model has several other limitations for predictive purposes because of the various assumptions used and possible uncertainties in input data.

Differences between measured and simulated water levels and salinity profiles are greater in some areas than others, which may reflect uncertainties in the recharge or withdrawal estimates, boundary conditions, assigned parameter values in the model, or representations of the different hydrogeological features in the model. Recharge estimates are based on water-budget computations that could be improved with a better understanding of the spatial distributions of rainfall, evapotranspiration, runoff, and land-cover characteristics. Improved recharge estimates in the study area will lead to improved estimates for parameter values in the numerical groundwater model and greater confidence in model results. Withdrawals represented in the model were based on available information. Unreported withdrawals and uncertainties in reported withdrawals that cannot be quantified also affect the model accuracy.

Results for the various withdrawal scenarios are based on the assumption that pumping rates can be varied as needed at each well. In reality, most of the wells are currently operated with single-speed pumps that are either on at the designed rate or off. Reduced withdrawal would have to be achieved by cycling the pumps on and off to maintain the desired average withdrawal rate or installing variable-speed drives on the pumps.

This report proposes no estimates or reevaluations of previous estimates of sustainable yield (Camp, Dresser & McKee Inc., 1982). Sustainable yield was defined for Guam as the maximum amount of water that can be continuously withdrawn from the freshwater lens without impairing the integrity of the lens and the water quality (Camp, Dresser & McKee Inc., 1982). The sustainable-yield approach is useful for providing a benchmark to managers and regulators and for keeping users aware that the resource is limited. This approach is limited, however, in that the definition of impairment is largely subjective and may involve a large number of criteria. Furthermore, the sustainable-yield estimates are based on the amount of acceptable quality water that might be obtainable from an ideal extraction system rather than being based on the infrastructure in place. In principle, to achieve production at 100 percent of sustainable yield, some of the consumers of the product would likely be getting water at the lowest quality deemed acceptable by whatever standard was agreed upon. Finally, the sustainable-yield estimates, which were based on some fraction of recharge, did not account for the dynamic responses of the aquifer system to withdrawal or natural changes in recharge (Bredehoeft, 2002).

Together, a numerical model and a comprehensive monitoring program can provide managers and regulators with the means for ongoing sustainable management of groundwater production. With such tools available, the old concept of "sustainable yield" has thus been superseded by "sustainable management." Sustainable management, it should be noted, is also a broader concept which, in addition to looking at ways to improve the efficiency of production and delivery as the resource use expands, also implies managing demand for the resource, supplying different levels of quality and quantity to meet different demands for different uses, and promoting conservation and efficiency of use.

Needs for Additional Study

The geometrical representation of the geologic units and contacts were simplified for the model. The geometric definition of the volcanic basement would likely be improved by using surface geophysical techniques in conjunction with drilling additional wells in the areas of greatest uncertainty (see Vann and others, 2013). For this study, areas of similar hydrologic conditions were represented as homogeneous zones of the same hydraulic conductivity. Zones of higher hydraulic conductivity undoubtedly exist as a result of fractures, conduits, caves, and other karst features developed throughout the NGLA, but their location and extent are poorly understood and cannot be represented specifically in this regional model. Improved estimates of the distribution of model parameters likely would lead to better model reliability.

Continued monitoring of water levels, salinity, and pumping rates will be useful to track the response of the groundwater resources to development and natural changes in recharge. Additional monitoring wells in areas lacking sufficient hydrologic data would be useful to help refine the model and for overall sustainable management of the water resource. Areas of need include locations downgradient of planned well locations in the Agafo Gumas and Andersen basins and downgradient of areas of the most withdrawal in the Finegayan, Mangilao, and Yigo-Tumon basins. Collection of geologic and hydrologic data for each new well drilled will provide new information about the aquifer and freshwater lens, such as the volcanic-basement position, the transition-zone thickness, and the hydraulic conductivity. Continued updates to the NGLA Database (Bendixson, 2013) as each new well is drilled will be invaluable for future hydrologic studies, continued refinement of the basement topography map (Vann and others, 2013), and updates to the numerical model. As additional data are gathered, especially in the Agafo Gumas and Andersen basins where data are sparse, the numerical model can be updated and refined to provide more confidence in the model results for these areas. Development of a well-planned monitoring-well network will make it possible to comprehensively sample groundwater for contaminants, which is important for ensuring a safe drinking-water supply and understanding contaminant transport processes.

The response of the freshwater lens to changes in recharge or sea level induced by future climate change was not addressed in this study. Preliminary projections from global climate models for the Western Pacific around Guam indicate little change in annual mean rainfall but a widespread increase in the number of heavy and extreme rain days and increases in potential evapotranspiration (Australian Bureau of Meteorology & CSIRO, 2011). The effects of these changes on future recharge estimates are unknown but potentially significant to future estimates of water availability. Additionally, sea level around Guam is projected to rise (Australian Bureau of Meteorology & CSIRO, 2011), potentially increasing the salinity of pumped water as the freshwater-lens position would be expected to move higher—bringing the transition zone closer to current pump intakes in the production wells. The effects on the freshwater lens from these potential changes could be investigated with the aid of the groundwater model.

A variety of questions about aquifer management also could be addressed with additional application of the model. Some such questions include the following:

- How will priorities be set for upgrading wells with variable speed drives?
- What threshold salinity should be specified for wells beyond which wells must be rested, and should the threshold vary by basin?
- Do certain basins recover more quickly or more slowly after a drought, and should they be managed differently?
- Can recharge be directed to critical areas to help maintain the freshwater lens?

Summary

Owing to population growth, freshwater demand on Guam has increased in the past and will likely increase in the future. During the early 1970s to 2010, groundwater withdrawals from the Northern Guam Lens Aquifer (NGLA), the main freshwater source on the island, tripled from about 15 to 45 million gallons per day (Mgal/d). By 2020, population growth on Guam is projected to add 23,000 people to the 2010 population, and a proposed military buildup in the near future includes the transfer of U.S. Marines and their dependents from Okinawa, Japan, to Guam. Because of the military relocation and population growth, freshwater demand on Guam is projected to increase substantially. The objectives of a 3.5-year study on the NGLA were to (1) advance the understanding of regional groundwater dynamics in the NGLA, (2) provide a new estimate of groundwater recharge for the entire island, and (3) develop a numerical groundwater flow and transport model for northern Guam that could serve as a tool to assist water-resource managers in estimating the effects of selected groundwater-pumping and climate scenarios on the water supply. This report describes (1) information related to the regional hydrologic system of the NGLA, (2) development of a numerical groundwater flow and transport model, and (3) results of model simulations assessing the hydrologic effects of various recharge and withdrawal conditions on the hydrologic system.

A three-dimensional numerical groundwater model capable of simulating density-dependent solute transport was developed as part of this study. The model used published estimates for most of the hydraulic conductivity, storage, and dispersivity values of limestone, in which the water occurs. Simulated water levels, pumped-well water salinities, and salinity profiles generally were in agreement with measured water levels, salinities, and salinity profiles from representative wells in the modeled area during 2010.

The numerical model constructed for this study was used to quantify changes in groundwater level and salinity for various withdrawal and recharge scenarios. Groundwater withdrawal scenarios included no withdrawal, withdrawal at 2010 rates, reduced withdrawal during drought, and increased withdrawal for selected growth projections. Recharge was either long-term average recharge or drought recharge. In general, the freshwater lens gets smaller when withdrawal increases or recharge is reduced during drought. Simulation results from the predevelopment (no pumping) scenario indicate the following for 2010 conditions (compared to predevelopment conditions) in the NGLA:

- water levels are more than 5 feet lower where freshwater in the limestone aquifer lies directly on the underlying volcanics and the freshwater lens is more than 50 feet thinner where the aquifer is thick enough to accommodate the extra freshwater thickness,
- water levels were up to 1 foot lower and the freshwater lens was thinner by 10–50 feet in most areas of the Yigo-Tumon basin,
- the freshwater lens was about the same size in the Agafo Gumas basin, and
- the seaward extent of para-basal water (freshwater in the limestone above volcanic rocks) shifted as much as 5,000 feet inland in the interior part of the Yigo-Tumon basin.

With respect to water yield, simulated salinities at selected Guam Water Authority (GWA) and Department of Defense (DoD) wells are classified, for the purposes of this study, as acceptable if they are below about 200 milligrams per liter (mg/L) chloride concentration (about 1-percent seawater salinity), cautionary if they are between 200 and 500 mg/L chloride concentration (1.0- and 2.6-percent seawater salinity), and threatened if they are greater than 500 mg/L chloride concentration (about 2.6-percent seawater salinity). Simulation results from the 2010 withdrawal scenario (40.3 Mgal/d) after a 5-year drought indicate the following:

- the amount of acceptable yield is reduced from 33.9 Mgal/d to 11.5 Mgal/d,
- the amount of cautionary yield increases from 4.1 Mgal/d to 17.8 Mgal/d,
- the amount of threatened yield increases from 2.2 to 11.0 Mgal/d, and
- the Yigo-Tumon basin has the highest amount of combined cautionary and threatened yield; representing about 79 percent of the total water pumped from this basin.

Reducing withdrawal at the highest salinity wells by about 8 Mgal/d during the drought scenario increased the amount of acceptable yield to 13.3 Mgal/d, increased the cautionary yield to 18.9 Mgal/d, and eliminated all threatened yield.

Five scenarios were used to investigate the results of projected groundwater withdrawals and proposed wells on the hydrologic system. The five scenarios are (1) projected rates and locations based on the most likely estimate of future conditions without the U.S. Marine Corps buildup, (2) the same conditions as scenario 1 but including the USMC buildup, (3) redistributing the DoD withdrawal in scenario 2 to lower salinity in some wells, (4) the same conditions as scenario 3 with a 5-year drought, and (5) the same conditions as scenario 2 but redistributing DoD and GWA wells to lower salinity.

Scenario 1—Simulation results from the most likely projected withdrawal scenario without the buildup (44.8 Mgal/d) indicate the following with respect to 2010 withdrawal rates:

- the total pumping rate increases by 4.5 Mgal/d,
- the amount of acceptable yield is 38.5 Mgal/d,
- the amount of cautionary yield is 3.72 Mgal/d,
- the amount of threatened yield is 2.58 Mgal/d, and
- 15 wells have chloride concentration increases greater than 10 mg/L, 12 in the Yigo-Tumon basin and 3 in the Finegayan basin.

Scenario 2—Simulation results from the most likely projected withdrawal scenario including the buildup (46.9 Mgal/d) indicate the following with respect to scenario 1 rates:

- the total pumping rate increases by 2.1 Mgal/d,
- the amount of acceptable yield is 39.9 Mgal/d,
- the amount of cautionary yield is 4.42 Mgal/d,
- the amount of threatened yield is 2.58 Mgal/d,
- 17 wells have chloride concentration increases greater than 10 mg/L; 8 wells in the Finegayan basin and 9 wells in the Agafo Gumas basin, and
- salinity from 3 wells increases from the acceptable to the cautionary salinity category.

Scenario 3—Redistributing the withdrawal (46.6 Mgal/d) from the DoD wells in scenario 2:

- lowers the amount of cautionary yield by 0.28 Mgal/d,
- lowers the amount of threatened yield by 0.3 Mgal/d, and
- increases the amount of acceptable yield to 40.2 Mgal/d.

Scenario 4—Simulation results from a drought scenario with the redistributed withdrawal scenario including the buildup (46.6 Mgal/d) indicate the following:

- the amount of acceptable yield is reduced to only 14.9 Mgal/d,
- the amount of cautionary yield increases to 19.61 Mgal/d, and
- the amount of threatened yield increases to 12.09 Mgal/d.

Scenario 5—A scenario in which projected groundwater withdrawal was redistributed in an attempt to maximize withdrawal and maintain acceptable salinities at DoD and GWA wells was determined by using the numerical model in an iterative manner. Redistributed withdrawals at existing wells were combined with withdrawal from the proposed new well sites. The redistribution simulates 46.51 Mgal/d of withdrawal from wells in the NGLA. Simulation results from this scenario indicate the following:

- the amount of acceptable yield is 41.4 Mgal/d,
- the amount of cautionary yield is 5.13 Mgal/d, and
- no pumped water is in the threatened yield category.

In general, increased withdrawal will result in lower water levels and increased salinity in nearby and downgradient wells. However, the extent of these effects for withdrawal rates greater than presented in this report has not been evaluated. The numerical model developed for this study simulates water levels and salinity on a regional scale and thus may not accurately predict either the pumped water level at an individual well or the salinity of water pumped from that well, but these values are still indicative of expected regional trends in water levels and salinity. Salinity of water pumped from a well may be controlled by local heterogeneities in the aquifer that are not represented in the model. The model has several other limitations for predictive purposes because of the various assumptions used and possible uncertainties in input data. Model reliability can be improved as the understanding of groundwater recharge, the distribution of the aquifer hydraulic values, and the geometry of the hydrologic features become better known through additional data collection.

References Cited

AECOM Technical Services, Inc., 2011, Guam water well testing study to support U.S. Marine Corps relocation to Guam, Final report: Prepared for the Department of the Navy Naval Facilities Engineering Command, Pacific, April 2011.

Andersen Air Force Base Environmental Review, 1995, Groundwater dye trace program and well cluster proposal for the landfill area: Mangilao, Guam, University of Guam Library, Final report.

Australian Bureau of Meteorology & CSIRO, 2011, Climate change in the Pacific—Scientific assessment and new research: v 1. Regional overview, v. 2, Country reports; 257 p., accessed August 29, 2013 at *http://www.cawcr.gov.au/projects/PCCSP*.

Ayers, J.F., and Clayshulte, R.N., 1984, A preliminary study of the hydrogeology of northern Guam: Mangilao, Guam, University of Guam, Water and Energy Research Institute of the Western Pacific, Technical Report No. 56, 77 p., available at *http://www.weriguam.org/reports/item/a-preliminary-study-of-the-hydrogeology-of-northern-guam.html.*

Bailey, R.T., Jenson, J.W., and Olsen, A.E., 2009, Numerical modeling of atoll island hydrogeology: Groundwater, v. 47, no. 2, p. 184–196.

Barner, W.L., 1995, Ground water flow in a young karst terrane developed along a coastal setting, northern Guam, Mariana Islands, *in* Seminar field course: Beldibi/Antalya, Turkey, International Research & Application Center for Karst Water Resources; Leesburg, Va., Karst Waters Institute [variously paged].

Barner, W.L., 1997, Time of travel in the fresh water lens of northern Guam, *in* Carew, J.L., ed., Proceedings of the Eighth Symposium on the Geology of the Bahamas and Other Carbonate Regions, San Salvador, Bahamas.

Barrett Consulting Group, 1992, Groundwater in northern Guam—Sustainable yield and groundwater development, final engineering report: Agana, Guam, May 1992.

Bendixson, V.M., 2013, The Northern Guam Lens Aquifer Database: Mangilao, Guam, University of Guam, Water and Environmental Research Institute of the Western Pacific, Technical Report No. 141, 45 p.

Bredehoeft, J.D., 2002, The water budget myth revisited—Why hydrogeologists model: Ground Water, v. 40, no. 4, p. 340–345.

Camp, Dresser & McKee Inc., 1982, Northern Guam lens study: Guam Environmental Protection Agency, Groundwater management program, Aquifer yield report prepared for the Government of Guam [variously paged].

Carlson, E., Doyle, D., and Smith, D., 2009, Development of comprehensive geodetic vertical datums for the United State Pacific Territories of American Samoa, Guam, and the Northern Marianas: Surveying and Land Information Science, v. 69, no. 1, p. 5–17.

Contractor, D.N., 1983, Numerical modeling of saltwater intrusion in the Northern Guam Lens: Water Resources Bulletin, v. 19, no. 5, p. 745–751.

Contractor, D.N., and Srivastava, R., 1990, Simulation of saltwater intrusion in the Northern Guam Lens using a microcomputer: Journal of Hydrology, v. 118, p. 87–106.

Contractor, D.N., and Jenson, J.W., 2000, Simulated effect of vadose infiltration on water levels in the Northern Guam Lens Aquifer: Journal of Hydrology, v. 229, p. 232–254.

Daly, C., and Halbleib, M., 2006, Pacific Islands (Guam) average monthly and annual precipitation, 1971–2000: PRISM Group at Oregon State University, accessed January 21, 2010, at *http://www.prism.oregonstate.edu/products/pacisl.phtml*.

Donnegan, J.A.; Butler, S.L.; Grabowiecki, Walter; Hiserote, B.A.; and Limtiaco, David, 2004, Guam's forest resources, 2002: U.S. Department of Agriculture, Forest Service, Resources Bulletin PNW-RB-243, 32 p.

Emery, K.O., 1962, Marine geology of Guam: U.S. Geological Survey Professional Paper 403–B, 76 p., available at *http://pubs.er.usgs.gov/publication/pp403B*.

Fosberg, F.R., 1960, The vegetation of Micronesia, 1. General descriptions, the vegetation of the Mariana Islands, and a detailed consideration of the vegetation of Guam: Bulletin of the American Museum of Natural History, v. 119, no. 1, 76 p., 40 pl.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 604 p.

Gingerich, S.B., 2003, Hydrologic resources of Guam: U.S. Geological Survey Water-Resources Investigations Report 03-4126, 2 pl., available at *http://pubs.usgs.gov/wri/wri034126/.*

Gingerich, S.B., 2008, Ground-water availability in the Wailuku area, Maui, Hawai‘i: U.S. Geological Survey Scientific Investigations Report 2008–5236, 95 p., available at *http://pubs.usgs.gov/sir/2008/5236/*.

Gingerich, S.B., and Engott, J.A., 2012, Groundwater availability in the Lahaina District, west Maui, Hawai‘i: U.S. Geological Survey Scientific Investigations Report 2012–5010, 90 p., available at *http://pubs.usgs.gov/sir/2012/5010/*.

Guam Environmental Protection Agency, 1986, Groundwater management program annual report: Agana, Guam, 141 p.

Guam Environmental Protection Agency, 2001, Guam Water Quality Standards 2001 Revision: Harmon, Guam, 122 p.

Guam Visitors Bureau, 2010, January 2010 Visitor statistics, accessed June 2011 at *http://visitguam.org/Runtime/GVBResearch.aspx*.

Guard, C.P., Hamnett, M.P., Neumann, C.J., Lander, M.A., and Siegrist, H.G., Jr., 1999, Typhoon vulnerability study for Guam: University of Guam, Water and Environmental Research Institute of the Western Pacific, Technical Report No. 85, 156 p., available at *http://www.weriguam.org/reports/item/typhoon-vulnerability-study-for-guam.html*.

Habana, N.C., Heitz, L.F., Olsen, A.E., and Jenson, J.W., 2009, Vadose flow synthesis for the Northern Guam Lens Aquifer: University of Guam, Water and Environmental Research Institute of the Western Pacific, Technical Report No. 127, 231 p., available at *http://www.weriguam.org/reports/item/vadose-flow-synthesis-for-the-northern-guam-lens-aquifer.html*.

Jenson, J.W., Keel, T.M., Mylroie, J.R., Mylroie, J.E., Stafford, K.W., Taboroši, D., and Wexel, C., 2006, Karst of the Mariana Islands—The interaction of tectonics, glacioeustasy, and freshwater/seawater mixing in island carbonates: Geological Society of America Bulletin 404 (Special Paper), p. 129–138.

Jocson, J.M.U., Jenson, J.W., and Contractor, D.N., 1999, Numerical modeling and field investigation of infiltration, recharge, and discharge in the Northern Guam Lens Aquifer: Mangilao, Guam, University of Guam, Water and Environmental Research Institute of the Western Pacific, Technical Report No. 88, 22 p., available at *http://www.weriguam.org/reports/item/numerical-modeling-and-field-investigation-of-infiltration-recharge-and-discharge-in-the-northern-guam-lens-aquifer.html*.

Jocson, J.M.U., Jenson, J.W., and Contractor, D.N., 2002, Recharge and aquifer response—Northern Guam Lens Aquifer, Guam, Mariana Islands: Journal of Hydrology, v. 260, p. 231–254.

Johnson, A.G., 2012, A water-budget model and estimates of groundwater recharge for Guam: U.S. Geological Survey Scientific Investigations Report 2012–5028, 53 p., available at *http://pubs.usgs.gov/sir/2012/5028/*.

Jones, I.C., and Banner, J.L., 2003, Estimating recharge thresholds in tropical karst island aquifers—Barbados, Puerto Rico and Guam: Journal of Hydrology, v. 278, p. 131–143.

Kubota, Hisayuki, and Wang, Bin, 2009, How much do tropical cyclones affect seasonal and interannual rainfall variability over the Western North Pacific?: Journal of Climate, v. 22, p. 5495–5510.

Lander, M.A., 1994, Meteorological factors associated with drought on Guam: Mangilao, University of Guam, Water and Energy Research Institute of the Western Pacific, Technical Report No. 75, 39 p., available at *http://www.weriguam.org/reports/item/meteorological-factors-associated-with-drought-on-guam.html*.

Lander, M.A., Jenson, J.W., and Beausoliel, Colette, 2001, Responses of well water levels on northern Guam to variations of rainfall and sea level: Mangilao, Guam, University of Guam, Water and Environmental Research Institute of the Western Pacific, Technical Report No. 94, 36 p.

Lander, M.A., and Guard, C.P., 2003, Creation of a 50-year rainfall database, annual rainfall climatology, and annual rainfall distribution map for Guam: Mangilao, Guam, University of Guam, Water and Environmental Research Institute Technical Report No. 102, 20 p. plus appendixes.

Longman, M.W., 1980, Carbonate diagenetic textures from near surface diagenetic environments: American Association of Petroleum Geologists Bulletin, v. 64, no. 4, p. 461–487.

Matson, E.A., 1993, Nutrient flux through soils and aquifers to the coastal zone of Guam (Mariana Islands): Limnology and Oceanography, v. 38, p. 361–371.

McDonald, M.Q., and Jenson, J.W., 2003, Chloride history and trends of water production wells in the Northern Guam Lens Aquifer: Mangilao, Guam, University of Guam, Water and Environmental Research Institute of the Western Pacific Technical Report No. 98, 67 p.

Meinzer, O.E., 1930, Ground water in the Hawai‘ian Islands, *in* Stearns, H.T., and Clark, W.O., Geology and water resources of the Kau District, Hawai‘i: U.S. Geological Survey Water-Supply Paper 616, p. 1–28, available at *http://pubs.er.usgs.gov/publication/wsp616*.

Mink, J.F., 1974, Groundwater resources of Guam—Occurrence and development: Report to the Public Utility Agency, Guam [variously paged].

Mink, J.F., 1976, Groundwater resources on Guam—Occurrence and development: Mangilao, Guam, University of Guam, Water and Energy Research Institute of the Western Pacific Technical Report No. 1, 276 p. (Reprinted 1991.), available at *http://www.weriguam.org/reports/item/groundwater-resources-of-guam-occurrence-and-development.html.*

Mink, J.F., 1991, Groundwater in Northern Guam—Sustainable yield and groundwater development: Barrett Consulting Group for Public Utility Agency of Guam.

Mink, J.F., and Vacher, H.L., 1997, Hydrogeology of northern Guam, *in* Vacher, H.L., and Quinn, T.M., eds., Geology and hydrogeology of carbonate islands: Amsterdam, Elsevier Science, Developments in Sedimentology 54, p. 743–761.

Moran, D.C., and Jenson, J.W., 2004, Dry trace of groundwater from Guam International Airport and Harmon Sink to Agana Bay and Tumon Bay: Mangilao, Guam, University of Guam, Water and Environmental Research Institute of the Western Pacific, Technical Report No. 97, 32 p., available at *http://www.weriguam.org/reports/item/dye-trace-of-groundwater-flow-from-guam-international-airport-and-harmon-sink-to-agana-bay-and-tumon-bay-guam.html.*

Mylroie, J.E., Jenson, J.W., Taboroši, D., Jocson, J.M.U., Vann, D.T., and Wexel, C., 2001, Karst features on Guam in terms of a general model of carbonate island karst: Journal of Cave and Karst Studies, v. 63, no. 1, p. 9–22.

National Climatic Data Center, 2010, Daily climate data for Guam, accessed March 24, 2010, at *http://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:GQW00041415/detail*.

NAVFAC Pacific, 2010, Related actions—Utilities and roadway projects, proposed action and alternatives—Potable water, *in* Final environmental impact statement, Guam and CNMI military relocation: Pearl Harbor, Hawai‘i, NAVFAC Joint Guam Program Office, v. 6, ch. 2.2, p. 2–26—2–50, available at *http://www.guambuildupeis.us/final_documents*.

National Oceanic and Atmospheric Administration, 2011, Gridded multibeam bathymetry of Guam Island, Guam U.S. Territory, accessed July 2012 at *http://www.soest.hawai‘i.edu/pibhmc/pibhmc_cnmi_gua_bathy.htm*.

National Oceanic and Atmospheric Administration, 2012, Apra Harbor, Guam, Marianas Islands historic tide data, accessed March 20, 2012, at *http://tidesandcurrents.noaa.gov/data_menu.shtml?bdate=19750101&edate=20110327&wl_sensor_hist=W5&relative=&datum=4&unit=1&shift=g&stn=1630000+Apra+Harbor%2C+Guam%2C+MARIANAS+ISLANDS&type=Historic+Tide+Data&format=View+Data*.

Oki, D.S., 2005, Numerical simulation of the effects of low-permeability valley-fill barriers and the redistribution of ground-water withdrawals in the Pearl Harbor Area, Oahu, Hawai‘i: U.S. Geological Survey Scientific Investigations Report 2005–5253, 111 p., available at *http://pubs.usgs.gov/sir/2005/5253/*.

Oki, D.S., 2008, The significance of accounting order for evapotranspiration and recharge in monthly and daily threshold-type water budgets: U.S. Geological Survey Scientific Investigations Report 2008–5163, 11 p., available at *http://pubs.usgs.gov/sir/2008/5163/*.

Paillet, F.L., Williams, J.H., Oki, D.S., and Knutson, K.D., 2002, Comparison of formation and fluid-column logs in a heterogeneous basalt aquifer: Ground Water, v. 40, no. 6, p. 577–585.

Partin, J.W., Jenson, J.W., Banner, J.L., Quinn, T.M., Taylor, F.W., Sinclair, D.J., Hardt, B. Lander, M., Bell, T., Miklavič, B., Jocson, J.M.U., and Taboroši, D, 2012. Relationship between modern rainfall variability, cave dripwater and stalagmite geochemistry in Guam, USA: Geochemistry, Geophysics, Geosystems, v. 13, Q03013, 2012, doi:10.1029/2011GC003930.

Peterson, F.L., and Gingerich, S.B., 1995, Modeling atoll groundwater systems, *in* El-Kadi, A.I., ed., Groundwater models for resources analysis and management: Boca Raton, Fla., CRC Press, p. 275–292.

Reagan, M.K., and Meijer, Arend, 1984, Geology and geochemistry of early arc-volcanic rocks from Guam: Geological Society of America Bulletin, v. 95, p. 701–713.

Rotzoll, Kolja, 2010, Effects of groundwater withdrawal on borehole flow and salinity measured in deep monitor wells in Hawai‘i—Implications for groundwater management: U.S. Geological Survey Scientific Investigations Report 2010–5058, 42 p., available at *http://pubs.usgs.gov/sir/2010/5058/*.

Rotzoll, Kolja, Gingerich, S.B., Jenson, J.W., and El-Kadi, A.I., 2013, Estimating hydraulic properties from tidal attenuation in the Northern Guam Lens Aquifer, territory of Guam, USA: Hydrogeology Journal, v. 21, no. 3, p. 643–654, doi:10.1007/s10040-012-0949-9.

Siegrist, H.G., and Randall, R.H., 1992, Carbonate geology of Guam: Proceedings of the Seventh International Coral Reef Symposium, June 18–20, Guam, USA, University of Guam Press, p. 1,195–1,216.

Siegrist, H.G., and Reagan, M.K., 2007, Geologic map and sections of Guam, Mariana Islands—Revision of original map from U.S. Geological Survey Professional Report 403–A (1964) by Tracey, J.I., Jr., Schlanger, S.O., Stark, J.T., Doan, D.B. and May, H.G.; field interpretations for 2008 revision assisted by Randall, R.H., and Jenson, J.W.: Mangilao, University of Guam, Water and Environmental Research Institute of the Western Pacific.

Simard, C.A., 2012, Analysis of salinity in the Northern Guam Lens Aquifer: Mangilao, University of Guam, M.S. thesis, 117 p.

Simard, C.A., Jenson, J.W., and Lander, M.A., 2013, Analysis of salinity in the Northern Guam Lens Aquifer: Mangilao, Guam, University of Guam, Water and Environmental Research Institute of the Western Pacific Technical Report No. 143, 65 p.

Sundstrom, R.W., 1947, Water resources of Guam: San Francisco, Department of the Army, Corps of Engineers, 52 p.

Taboroši, D., Jenson, J.W., Jocson, J.M.U., and Mylroie, J.E., 2009, Coastal discharge features from an uplifted coastal island aquifer, Northern Guam, Northern Mariana Islands, 15th International Congress of Speleology, July 19–25, Kerrville, Tex.: v.2, p. 548-553.

Taboroši, D, Jenson, J.W., and Mylroie, J.E., 2013, Field observations of coastal discharge from an uplifted carbonate island aquifer, northern Guam, Mariana Islands—A descriptive geomorphic and hydrogeologic perspective: Journal of Coastal Research v. 29, no. 4, p. 926 – 943, *http://dx.doi.org/10.2112/JCOASTRES-D-12-00054.1* .

Tracey, J.I., Jr., Schlanger, S.O., Stark, J.T., Doan, D.B., and May, H.G., 1964, General geology of Guam: U.S. Geological Survey Professional Paper 403–A, 104 p., 3 pl., available at *http://pubs.er.usgs.gov/publication/pp403A*.

U.S. Census Bureau, 2011, Table 1313, Estimated resident population with projections: Statistical Abstract of the United States; 2010, Puerto Rico and the Island Areas, accessed May 19, 2011, at *http://www.census.gov/compendia/statab/cats/puerto_rico_the_island_areas.html*.

U.S. Department of Agriculture, 1999, Northern Guam resource report—Ground water protection: Maite, Guam, 71 p. plus appendixes.

U.S. Department of Agriculture, 2006, Detailed vegetation map for the Island of Guam: Forest Service Region 5, State and Private Forestry, Forest Health Protection, accessed March 29, 2010, at *http://www.fs.fed.us/r5/spf/fhp/fhm/landcover/islands/index.shtml*.

Vacher, H.L., and Mylroie, J.E., 2002, Eogenetic karst from the perspective of an equivalent porous medium: Carbonates and Evaporites, v. 17, no. 2, p. 182–196.

Vann, D.T., Bendixson, V.M, Roff, D.F., Habana, N.C., Simard, C.A., Schumann, R.M., and Jenson, J.W., 2013, Topography of the basement rock beneath the Northern Guam Lens Aquifer and its implications for groundwater exploration & development: Mangilao, Guam, University of Guam, Water and Environmental Research Institute of the Western Pacific, Technical Report No. 142, in press.

Voss, C.I., 1999, USGS SUTRA code—History, practical use, and application in Hawai‘i, *in* Bear, J., Cheng, AH-D., Sorek, S., Ouzar, D., and Herrera, I., eds., Seawater intrusion in coastal aquifers—Concepts, methods, and practices: Boston, Kluwer Academic Publishers, p. 249–313, doi:10.1007/978-94-017-2969-7_9

Voss, C.I., and Provost, A.M., 2002 (Version of September 22, 2010), SUTRA, A model for saturated-unsaturated variable-density ground-water flow with solute or energy transport: U.S. Geological Survey Water-Resources Investigations Report 02–4231, 291 p., available at *http://water.usgs.gov/nrp/gwsoftware/sutra/SUTRA_2_2-documentation.pdf*.

Ward, P.E., Hoffard, S.H., and Davis, D.A., 1965, Hydrology of Guam: U.S. Geological Survey Professional Paper 403–H, 28 p., 1 pl., available at *http://pubs.usgs.gov/pp/0403h/report.pdf*.

Winston, R.B., and Voss, C.I., 2003, SutraGUI, a graphical-user interface for SUTRA, a model for ground-water flow with solute or energy transport: U.S. Geological Survey Open-File Report 03–285, 114 p., software available at *http://water.usgs.gov/nrp/gwsoftware/sutra.html*.

Young, F.J., 1988, Soil survey of Territory of Guam: U.S. Department of Agriculture, Soil Conservation Service, 166 p., available at *http://soildatamart.nrcs.usda.gov/Manuscripts/PB640/0/guam.pdf*.

Appendix 1. Properties of wells in the numerical model of the Northern Guam Lens Aquifer, Guam

Table 1–1. Properties of wells in the numerical model of the Northern Guam Lens Aquifer, Guam.

[Well locations and open intervals modified from Bendixson (2013); Maui-type shafts are generally open from above the water table to several feet below the water table; –, not applicable]

Well name	Altitude of top of open interval (feet relative to sea level)	Altitude of bottom of open interval (feet relative to sea level)	Length of horizontal shaft (feet)
A-01	–0.3	–154	–
A-02	–0.3	–52	–
A-03	–0.3	–282	–
A-04	–0.3	–161	–
A-05	–0.3	–184	–
A-06	–0.3	–154	–
A-08	–0.3	–180	–
A-09	–0.3	–52	–
A-10	–0.3	–26	–
A-12	–0.3	–253	–
A-13	–0.3	–197	–
A-14	–19.7	–52	–
A-15	–0.3	–33	–
A-16	49.2	16	–
A-17	–0.3	–52	–
A-18	–19.7	–56	–
A-19	–0.3	–28	–
A-20	49.2	–3	–
A-21	–3.3	–62	–
A-23	–0.3	–49	–
A-25	–0.3	–10	–
A-26	–0.3	–46	–
A-30	–0.3	–52	–
A-31	–0.3	–56	–
ACEORP	6.6	–3	700
AECOM-1	6.6	–38	–
AECOM-2	–0.3	–39	–
AECOM-3	6.6	–177	–
AECOM-7	6.6	–31	–
AECOM-9	6.6	–246	–
AECOM-11	6.6	–37	–
AF-01	–0.3	–36	–
AF-02	–0.3	–36	–
AF-03	–0.3	–36	–
AF-04	–0.3	–36	–
AF-05	–0.3	–36	–
AG-01	–0.3	–26	–
AG-02	–0.3	–66	–
AG-10	–0.3	–33	

Table 1–1. Properties of wells in the numerical model of the Northern Guam Lens Aquifer, Guam.—Continued

[Well locations and open intervals modified from Bendixson (2013); Maui-type shafts are generally open from above the water table to several feet below the water table; –, not applicable]

Well name	Altitude of top of open interval (feet relative to sea level)	Altitude of bottom of open interval (feet relative to sea level)	Length of horizontal shaft (feet)
BPM	–0.3	–43	–
BPM-01	6.6	–33	–
D-01	–0.3	–36	–
D-02	–0.3	–36	–
D-04	–0.3	–23	–
D-05	–0.3	–30	–
D-06	–0.3	–36	–
D-07	–0.3	–52	–
D-08	–26.2	–36	–
D-09	–0.3	–56	–
D-10	–0.3	–26	–
D-11	–0.3	–20	–
D-12	–0.3	–52	–
D-13	–39.4	–59	–
D-14	–0.3	–59	–
D-15	–0.3	–49	–
D-16	–0.3	–46	–
D-19	–0.3	–49	–
D-20	–0.3	–36	–
D-21	–0.3	–49	–
D-24	–16.4	–66	–
D-25	–0.3	–46	–
D-26	–0.3	–59	–
D-28	–0.3	–16	–
EX-01	6.6	–502	–
EX-04	6.6	–246	–
EX-05A	–0.3	–23	–
EX-07	6.6	–417	–
EX-08	6.6	–187	–
EX-09	6.6	–266	–
EX-11	–0.3	–72	–
F-01	–0.3	–72	–
F-02	0.3	–36	–
F-03	–0.3	–39	–
F-04	–0.3	–33	–
F-05	–0.3	–36	–
F-06	–0.3	–36	–
F-07	–0.3	–59	–
F-08	–0.3	–26	–

Table 1–1. Properties of wells in the numerical model of the Northern Guam Lens Aquifer, Guam.—Continued

[Well locations and open intervals modified from Bendixson (2013); Maui-type shafts are generally open from above the water table to several feet below the water table; –, not applicable]

Well name	Altitude of top of open interval (feet relative to sea level)	Altitude of bottom of open interval (feet relative to sea level)	Length of horizontal shaft (feet)
F-09	–0.3	–26	–
F-10	–0.3	–49	–
F-11	–6.6	–49	–
F-12	–0.3	–43	–
F-13	–0.3	–52	–
F-15	–14.8	–52	–
F-16	–0.3	–49	–
F-17	–0.3	–49	–
F-19	–0.3	–62	–
F-20	–0.3	–33	–
FFH-08	–0.3	–59	–
FM-01	–0.3	–52	–
GH-501	–0.3	–23	–
GHURA	–0.3	–56	–
GPH	–0.3	–39	–
H-01	0.3	–16	–
HGC-02	–0.3	–56	–
HGC-03	–0.3	–49	–
HRP-01	–0.3	–23	–
HRP-02	–0.3	–26	–
M-01	–0.3	–36	–
M-02	–0.3	–59	–
M-03	–0.3	–49	–
M-04	–0.3	–49	–
M-05	–0.3	–56	–
M-06	–0.3	–79	–
M-07	–0.3	–52	–
M-08	–0.3	–36	–
M-09	–0.3	–75	–
M-10A	6.6	–16	–
M-12	–0.3	–52	–
M-15	–0.3	–52	–
M-17B	–0.3	–43	–
M-18	–0.3	–36	–
M-20A	–0.3	–33	–
M-21	–0.3	–39	–
M-23	–0.3	–75	–

Table 1–1. Properties of wells in the numerical model of the Northern Guam Lens Aquifer, Guam.—Continued

[Well locations and open intervals modified from Bendixson (2013); Maui-type shafts are generally open from above the water table to several feet below the water table; –, not applicable]

Well name	Altitude of top of open interval (feet relative to sea level)	Altitude of bottom of open interval (feet relative to sea level)	Length of horizontal shaft (feet)
MGC-04	–0.3	–26	–
MW-01	–0.3	–43	–
MW-02	6.6	–30	–
MW-03	–0.3	–13	–
MW-05	–0.3	–36	–
MW-06	–0.3	–36	–
MW-07	–0.3	–43	–
MW-08	–0.3	–39	–
MW-09	–0.3	–39	–
NAS-01	–0.3	–69	–
NCS-03	6.6	–16	–
NCS-06	–0.3	–16	–
NCS-07	–0.3	–16	–
NCS-09	–0.3	–16	–
NCS-10	–0.3	–36	–
NCS-11	–0.3	–36	–
NCS-12	–0.3	–36	–
NCS-A	–9.8	–36	–
NCS-B	–0.3	–16	–
NRMC-01	–0.3	–16	–
NRMC-02	–0.3	–16	–
NRMC-03	–0.3	–16	–
PBI-01	–0.3	–46	–
PIC	–0.3	–33	–
PW01	–0.3	–39	–
PW07	–0.3	–39	–
PW11	–0.3	–39	–
PW14	–0.3	–39	–
PW16	–0.3	–39	–
PW18	–0.3	–39	–
PW57	–0.3	–39	–
Site08	–0.3	–33	–
Site12	–0.3	–33	–
Tumon	–0.3	–7	1,000
Y-01	–0.3	–36	–
Y-02	–0.3	–49	–
Y-03	–0.3	–52	–

Table 1–1. Properties of wells in the numerical model of the Northern Guam Lens Aquifer, Guam.—Continued

[Well locations and open intervals modified from Bendixson (2013); Maui-type shafts are generally open from above the water table to several feet below the water table; –, not applicable]

Well name	Altitude of top of open interval (feet relative to sea level)	Altitude of bottom of open interval (feet relative to sea level)	Length of horizontal shaft (feet)
Y-04	–0.3	–46	–
Y-05	–0.3	–46	–
Y-06	–0.3	–49	–
Y-07	–0.3	–62	–
Y-09	–0.3	–52	–
Y-10	–0.3	–56	–
Y-12	–0.3	–39	–
Y-14	–0.3	–36	–
Y-16	–0.3	–39	–
Y-18	–0.3	–36	–
Y-19	–0.3	–36	–
Y-20	–0.3	–49	–
Y-21	–0.3	–39	–
Y-22	–0.3	–56	–

For additional information regarding this publication, contact:

Director
USGS Pacific Islands Water Science Center
677 Ala Moana Blvd., Suite 415
Honolulu, HI 96813
(808) 587-2400
email: dc_hi@usgs.gov

Or visit the USGS Pacific Islands Water Science Center Web site at:
http://hi.water.usgs.gov

Prepared by:
USGS Science Publishing Network
Raleigh Publishing Service Center
3916 Sunset Ridge Road
Raleigh, NC 27607

Gingerich—**The Effects of Withdrawals and Drought on Groundwater Availability in the Northern Guam Lens Aquifer, Guam**—Scientific Investigations Report 2013–5216

ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20135216