# SALINITY IN THE NORTHERN GUAM LENS AQUIFER

**with online data appendix**


by

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Nathan C. Habana



WERI
WATER AND ENVIRONMENTAL RESEARCH INSTITUTE
OF THE WESTERN PACIFIC
UNIVERSITY OF GUAM

Technical Report No. 143

April 2015

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**Technical Report No. 143**
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**Acknowledgements:** The work reported herein was funded by the Guam Hydrologic Survey (Award no. 10-30-430002-R-5) and the Department of Interior via the Water Resources Research Institute Program of the U.S. Geological Survey (Award no. 63-2K-433017-R-5) administered through the Water and Environmental Research Institute of the Western Pacific at the University of Guam.

## Author Contributions

C.A. Simard compiled the data, conducted statistical and spatial analyses, and interpreted trends and their relationships to geological conditions and meteorological phenomena.

J.W. Jenson and M.A. Lander were principal investigators for the project and thesis advisors to C.A. Simard.

R.M. Manzanilla, D.G. Superales, and N.C. Habana recompiled the trend analysis for each record, integrating it into the *Northern Guam Lens Aquifer Database (WERI Technical Report #141)*, uploading it into the Guam Hydrologic Survey website, and preparing the database for ongoing updates to track future trends.

## Recognitions

This report is derived from C.A. Simard's research thesis, *Comprehensive Analysis of Salinity Trends in the Northern Guam Lens Aquifer*, for which she was awarded a Master of Science degree in Environmental Science by the University of Guam in May 2012. Her thesis received the 2012 *University of Guam President's Award* for the outstanding graduate thesis of the academic year.

The project was subsequently selected by the *National Institutes for Water Resources* (NIWR) for its 2013 *National Impact Award*. The annual award recognizes the NIWR-sponsored project which, among all others completed nationwide, shows the most promise to "yield significant improvement in the nation's water supply."

## ABSTRACT

This study is the most comprehensive historical evaluation to date of the factors contributing to changes in groundwater salinity in the Northern Guam Lens Aquifer. Spatial patterns and temporal trends observed in production and monitoring wells were compared with records of rainfall, sea level, and the Southern Oscillation Index (SOI), as well as historical pumping rates. Data included chloride concentrations reported for production wells for which records exist from 1973 through 2010, and specific conductance measurements from aquifer monitoring wells over the six years from 2005 through 2010 in the three basins instrumented with monitoring wells that penetrate the depth of the freshwater lens. (The other three of the aquifer's six basins are not similarly instrumented.)

The study examined records from 153 wells in the aquifer's six basins: 118 production wells operated by Guam Waterworks Authority (GWA) (formerly the Public Utility Agency of Guam (PUAG)); 25 production wells owned and operated by the Naval Facilities Engineering Command Marianas (NAVFACMAR); 11 freshwater production wells under private ownership; 9 test borings and 2 monitoring wells recently installed in 2010 by NAVFACMAR; and 12 publically-owned monitoring wells instrumented and monitored by the University of Guam's Water & Environmental Research Institute of the Western Pacific (WERI) and the U.S. Geological Survey (USGS) under a local-federal cost-sharing agreement. Chloride concentration has historically been the primary parameter for monitoring groundwater salinity on Guam. This study builds on the 2003 report by McDonald and Jenson, *Chloride History and Trends of Water Production Wells in the Northern Guam Lens Aquifer*, with the addition of chloride data for the 12 years from 1999 through 2010, and the inclusion of records from Air Force and private freshwater production wells.

Chloride concentrations in production wells showed significantly increasing trends over the period of record at 107 (70%) of the 153 wells. Increasing groundwater salinity in the supra-basal groundwater zone, which is not hydraulically connected to underlying saltwater, suggests that other sources of chloride, such as dissolved salts in rainfall, sea spray, or man-made sources, are affecting the aquifer. Comparison of chlorides with the SOI revealed that chloride increases occur during the transition from El Niño to La Niña episodes, and that chloride decreases occur during the transition from La Niña to El Niño episodes. Some production wells exhibit a cyclical chloride trend with a 4-year to 6-year periodicity that appears to coincide with the El Niño/Southern Oscillation.

In the two basins that contain monitoring wells that penetrate the entire lens (so-called "deep wells"), specific conductance data show an upward trend during the unusually dry years from 2005 through 2010. In the Yigo-Tumon Basin, the freshwater lens showed an overall thinning of about 2-6 meters (5-16% of lens thickness). Over the same period, the lens in the Hagåtña Basin thinned by 5-16 meters (7-19%). At the monitoring wells in the Yigo-Tumon Basin, the prime layer (defined as groundwater with less than 250 mg/l chloride) thinned by about 3-8 meters (5-24%). In the southern region of the Hagåtña Basin, containing the Hagåtña Argillaceous Limestone, the prime layer fluctuates seasonally on the order of 70 meters, reaching its thinnest point (at a few meters depth) during the dry season (January to June) and thickest point (~70 meters) during the wet season (July to December).



**Keywords: Northern Guam Lens Aquifer, chloride trends, saltwater contamination**

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NOTE: Units cited in this report reflect the units in which the data have been collected and reported. Meteorological, engineering, and construction data are thus given in English units. Other data, including hydrologic well data collected and reported by the US Geological Survey, are given in Standard International Units.

# SALINITY IN THE NORTHERN GUAM LENS AQUIFER

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*Manzanilla, R.M., Superales, D.G., and Habana, N.C.*

## 1 INTRODUCTION

### 1.1 Statement of the Problem

The Northern Guam Lens Aquifer (NGLA) produces about 90% of the island's drinking water. Extraction of fresh water from the aquifer, however, must be planned and managed to minimize the risk of contaminating it with unacceptably high concentrations of salt from the underlying saltwater. Identifying and understanding the different variables that control spatial distribution and temporal trends in salinity, and their relative contributions to salinity of Guam's freshwater supply are essential for developing appropriate sustainable management approaches. To better understand spatial patterns and temporal trends in salinity in the various wells and sectors of the Northern Guam Lens Aquifer, we have examined the entire historic salinity dataset, applying our current understanding of aquifer hydrogeology and local climatic history. We present observations and findings to help determine the extents to which natural as well as human-induced processes are affecting groundwater salinity, and recommend steps to manage the salinity of Guam's drinking water.

### 1.2 Objectives of Study

The three specific objectives of this study were to:

1. Evaluate recent and historical salinity trends in the NGLA, as measured by chloride concentrations (Appendix A) reported in production wells from 1973 through 2010, and by specific conductance measurements reported for monitoring wells from 2005 through 2010;
2. Identify natural and management factors potentially influencing salinity across the NGLA; and
3. Based on the outcomes of this study, offer recommendations for aquifer management and future studies.

### 1.3 Northern Guam Lens Aquifer

#### General Geology

Guam is the largest and southernmost of the Northern Mariana Islands, situated at 13°30′N and 144°45′W in the western Pacific Ocean. The northwest-southeast trending Pago-Adelup fault divides Guam into two physiographic provinces, a southern volcanic upland and a northern limestone plateau, overlying the volcanic basement (Figure 1). The northern limestone plateau slopes generally to the southwest, and ranges in elevation from 500 to 600 feet along the northern coast to 200 feet adjacent to the Pago-Adelup fault. Steep limestone cliffs and narrow coastal terraces rim the northern coastline, with some modern fringing reefs occupying near-shore ocean waters.

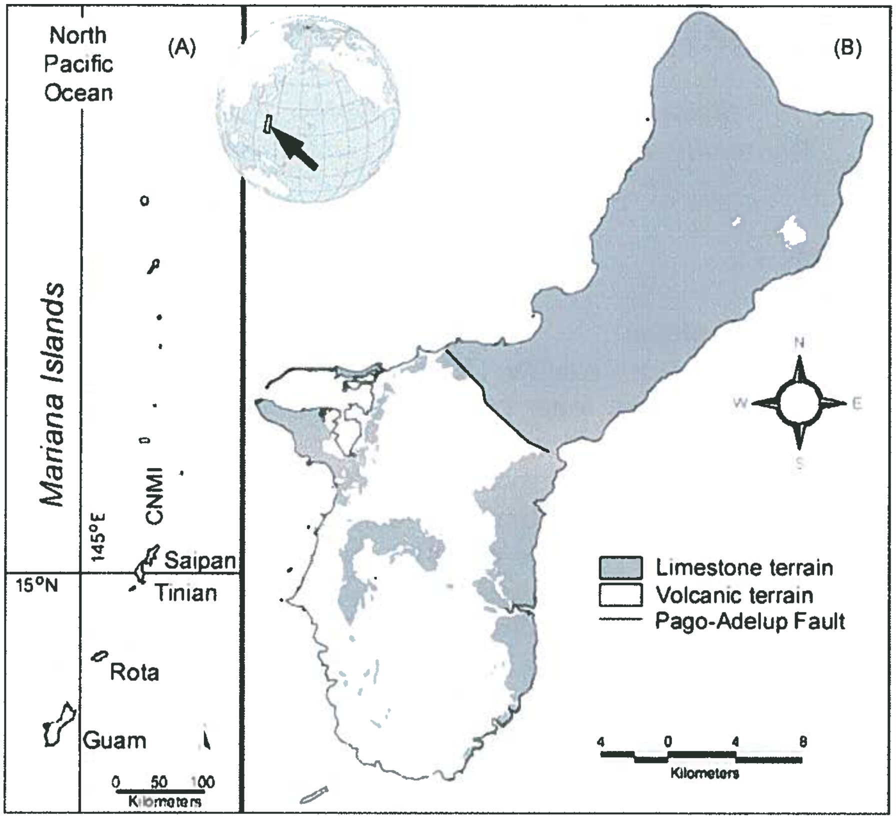


**Figure 1**: Location (A) and physiographic provinces (B) of Guam (with permission, Taboroši et al., 2005).

The principal aquifer rock units of northern Guam are the Barrigada Limestone and Mariana Limestone, as first mapped by Tracey et al. (1964). The Barrigada Limestone is a massive, typically friable detrital limestone, deposited in a former deep-water environment, which overlies the volcanic basement and comprises most of the bedrock of northern Guam. Only a ring-shaped outcrop of Barrigada Limestone is exposed at the surface in the north-central region (Appendix B). The Mariana Limestone is formed from reef and lagoon materials, which cap most of the surface and perimeter of the northern plateau. The Mariana Limestone is divided into two members: the main member, uncontaminated by clay, and the Hagåtña Argillaceous Member containing variable amounts of clay originating from the adjacent volcanic uplands (Tracey et al. 1964). Clay is present throughout the argillaceous limestone matrix (up to 5%) and contained in pockets and cavities (up to 20%) (Taboroši 2006).

Weathered volcanic basement rocks protrude above the limestone bedrock at Mt. Santa Rosa (858 feet elevation) and Mataguac Hill (630 feet elevation). The basement rock rises above sea level at Barrigada Hill (665 feet elevation) but is entirely covered by limestone (Tracey et al. 1964). Minor outcrops of Janum Limestone and Merizo Limestone are exposed in coastal areas, and minor outcrops of Alifan Limestone are exposed near Mt. Santa Rosa and north-northeast of the Pago-Adelup fault. A simplified geologic map of Guam, showing locations of production wells, hydrologic monitoring wells, and recent test borings, is included in Appendix B.

**General Hydrogeology**

Guam receives about 100 inches of rainfall annually, which is split 69% during the wet season (July to December) and 31% during the dry season (January to June) (Lander 1994). The most recent comprehensive water-budget study of Guam (Johnson, 2012), estimates that about 50% of total rainfall on the NGLA is lost to evapotranspiration while the remaining 50% is captured as recharge. Rainfall infiltrates the limestone either through diffuse flow during light to moderate rainfall events or as concentrated fast flow through fractures and conduits during heavy rainfall events (Jocson et al., 2002). Rainfall onto the much less permeable volcanic terrain of Mt. Santa Rosa and Mataguac Hill enters the subsurface via streams that sink at volcanic-limestone contacts (Taboroši et al. 2005). In the Hagåtña Basin, decreased permeability associated with the higher clay content of the argillaceous limestone allows for perennial surface waters to flow in the Hagåtña, Chaot, Fonte, and Pago rivers.

Within the limestone bedrock, a thin layer of fresh water floats on relatively denser saltwater in the *basal groundwater zone*, or overlies the impermeable volcanic basement rock in the *para-basal* and *supra-basal groundwater* zones. A cross-sectional view of the NGLA is presented in Figure 2. Within the basal zone, the boundary between variable density freshwater and saltwater is a gradational mixing zone. The intersection of the freshwater-saltwater mixing zone with the volcanic basement is called the *saltwater toe* (CDM 1982b). Within the para-basal zone, the freshwater lens is underlain by volcanic basement below mean sea level (MSL). Within the supra-basal zone, fresh water descending to the lens is underlain by volcanic basement above MSL (AECOM 2011).

The first operative map of volcanic basement topography was produced by the 1982 Northern Guam Lens Study (CDM 1982) from borehole and seismic data. The 1982 map divided the NGLA into six groundwater basins (termed *sub-basins* at the time).[1] Vann (2000, 2011) revised the original map by incorporating subsequent geophysical data (from Mink 1991) and borehole data from ongoing groundwater exploration projects. Vann et al. (2014) recently completed a comprehensive update to the map, incorporating the latest borehole data (including results from AECOM Technical Services 2011) (Figure 3).

The geologically young limestones of northern Guam have not been extensively compacted or cemented, but have undergone extensive freshwater diagenesis (Jocson et al.

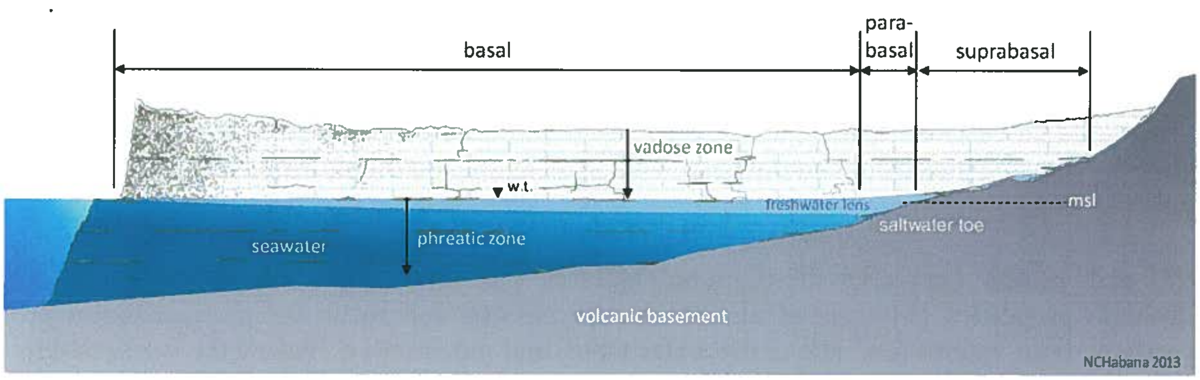


**Figure 2**: Cross-sectional schematic of the Northern Guam Lens Aquifer. (Vertical scale greatly exaggerated.)

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[1] The aquifer basins are analogous to separate surface watershed basins, but differ in that part of the boundaries between them consist of flow lines, which can shift in response to redistributions of pumping or recharge. (See Figure 3.)

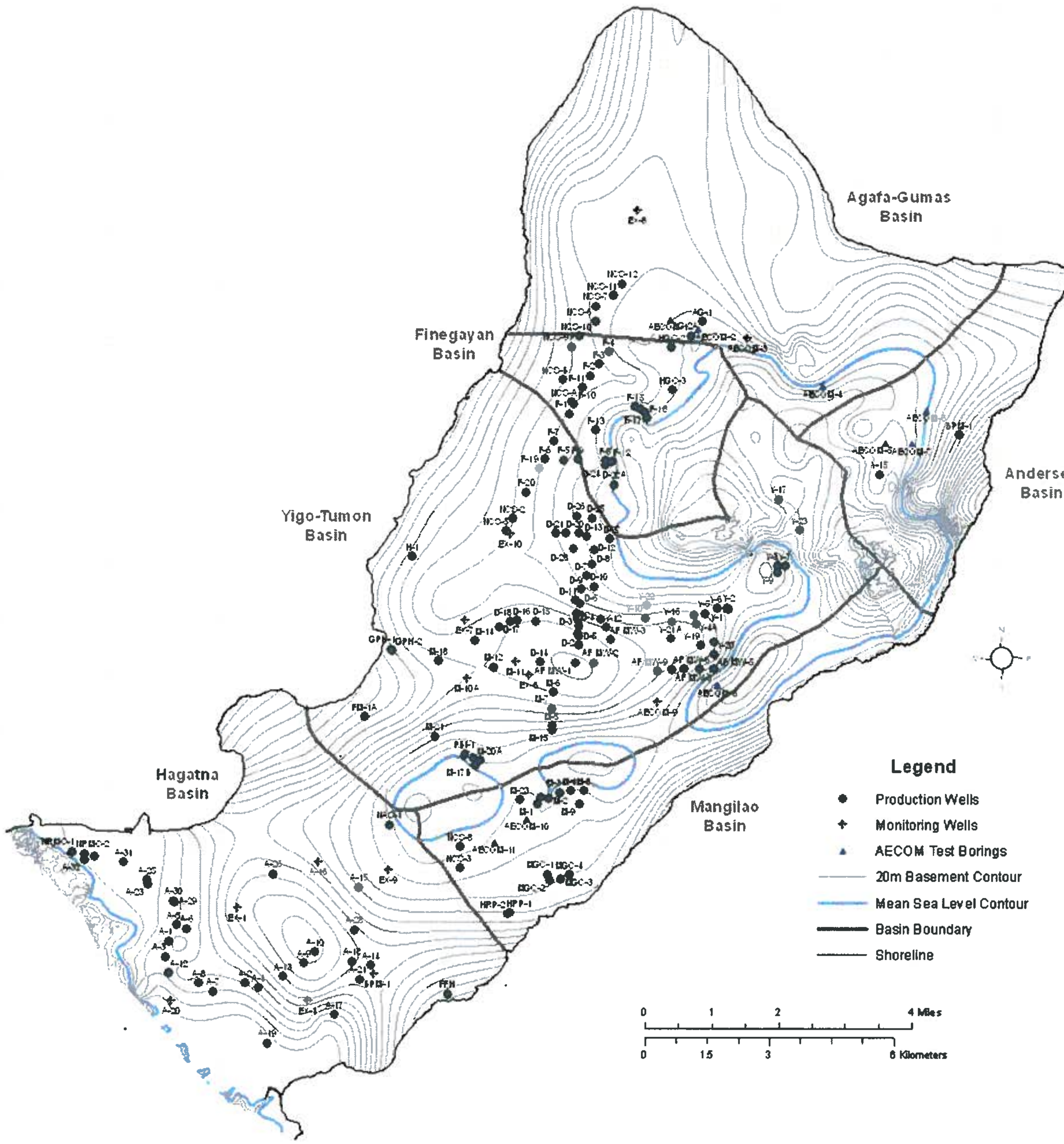


**Figure 3**: Volcanic basement contour map, with production and monitoring wells. (From Vann et al. 2014.)

1999) and exhibit pervasive dissolutional features that have important effects on their hydrologic properties (Mylroie et al. 2001). Successive and recurring reorganization of porosity by both vadose (i.e., above the water table) and phreatic (i.e., below the water table) freshwater diagenesis has created a complex triple-porosity aquifer with *matrix porosity*, *fracture porosity*, and *conduit porosity*.

As the freshwater lens has migrated up and down over geologic time, conduit networks have formed along the bedrock-basement (limestone-volcanic) contacts during vadose conditions. During prolonged sea-level still-stands, networks of interconnected voids have formed at the water table and possibly along the bottom of the lens as well (Vacher and

Mylroie 2002). Conduits and caves formed at past sea levels are present throughout the vadose zone and in the phreatic zone, down to at least the lowest of the Pleistocene sea levels (probably about 400 feet below modern sea level, and well below the base of the modern freshwater lens). Freshwater discharges on the coast from springs and seeps, and from fractures and caves (Taboroši 2006; Taboroši et al. 2013).

Hydraulic conductivity, and thus the rate of water movement through the aquifer, are highly variable on regional and local scales in the triple-porosity NGLA. Clay content within the limestone strongly affects its hydraulic conductivity. Regional hydraulic conductivities estimated from modeling (Gingerich 2013) range from 4,000 feet per day (ft/d) in the argillaceous limestone, to 90,000 ft/day in clean limestone. Local hydraulic conductivities estimated from pump tests range from 20 ft/day in the argillaceous limestone compared to 2,000 ft/d in clean limestone (Mink and Vacher 1997).

**NGLA Wells**

This study evaluated data from 118 production wells operated by Guam Waterworks Authority (GWA) (formerly the Public Utility Agency of Guam (PUAG)); 25 production wells owned and operated by the Naval Facilities Engineering Command Marianas (NAVFACMAR); 11 freshwater production wells under private ownership; 9 test borings and 2 monitoring wells recently installed by NAVFACMAR; and 12 publically-owned observation wells instrumented and monitored by the University of Guam's Water & Environmental Research Institute of the Western Pacific (WERI) and the U.S. Geological Survey (USGS) (Figure 3 and Table 1).

<u>Production Wells</u>

Hundreds of boreholes have been drilled into the NGLA since the United States Navy brought the first drill rig to Guam in 1937 (Bendixson et al. 2014). Because of limited understanding of the occurrence and dynamic behavior of the groundwater in the aquifer at the time, wells were often arbitrarily located and/or set too deep, so that many boreholes were never brought into production, or failed as production wells, due to poor performance and/or elevated salinity (Mink 1976). By the summer of 1974, 57 production wells were extracting approximately 15 million gallons per day (mgd) of groundwater from the NGLA (Mink 1976). By the end of 2009, 136 municipal, military, and private production wells were extracting approximately 43 mgd of groundwater from the NGLA (excluding private saltwater production wells).

<u>Monitoring Wells</u>

In 1998, the 24th Guam Legislature enacted Public Law No. 24-161 to create the Guam Comprehensive Water Monitoring Program (CWMP) to collect and compile data on Guam's water resources. The program restarted systematic data collection that had been abandoned several years earlier because of a discontinuance of funding. Annual appropriations from the Guam legislature for the CWMP support a collaborative program between the University of Guam's Water and Environmental Research Institute of the Western Pacific and the US Geological Survey's Pacific Island Water Science Center to collect and archive water resource data on Guam. Also established in 1998, under Public Law 24-247, was the Guam Hydrologic Survey (GHS) Program, which is tasked to consolidate and analyze hydrologic data, conduct research into selected water problems, and prepare reports documenting water use, trends, and concerns on Guam (Jenson and Jocson 1998). Groundwater monitoring wells (Figure 3) currently maintained under the CWMP and GHS programs are situated in the Agafa Gumas, Hagåtña, and Yigo-Tumon Basins. There are no similar monitoring wells in the Andersen, Finegayan or Mangilao Basins.

**Table 1**: List of production and monitoring wells, according to basin, used in this study.

| Well Name | Well Type | Owner |
|---|---|---|
| **Agafa-Gumas Basin** | | |
| AECOM-1 | Test Boring | NAVFACMAR |
| AECOM-2 | Monitoring | NAVFACMAR |
| AECOM-3 | Monitoring | NAVFACMAR |
| AECOM-4 | Test Boring | NAVFACMAR |
| AG-1 | Production | GWA |
| AG-2A | Production | GWA |
| EX-8 | Monitoring | CWMP |
| NCS-6 | Production | NAVFACMAR |
| NCS-7 | Production | NAVFACMAR |
| NCS-11 | Production | NAVFACMAR |
| NCS-12 | Production | NAVFACMAR |
| **Andersen Basin** | | |
| AECOM-5 | Test Boring | NAVFACMAR |
| AECOM-6 | Test Boring | NAVFACMAR |
| AECOM-7 | Test Boring | NAVFACMAR |
| BPM-1 | Irrigation | NAVFACMAR |
| Y-15 | Production | GWA |
| **Finegayan Basin** | | |
| D-22A | Production | GWA |
| D-24 | Production | GWA |
| F-1 | Production | GWA |
| F-2 | Production | GWA |
| F-3 | Production | GWA |
| F-4 | Production | GWA |
| F-8 | Production | GWA |
| F-10 | Production | GWA |
| F-11 | Production | GWA |
| F-12 | Production | GWA |
| F-13 | Production | GWA |
| F-15 | Production | GWA |
| F-16 | Production | GWA |
| F-17 | Production | GWA |
| F-18 | Production | GWA |
| HGC-2 | Production | GWA |
| HGC-3 | Irrigation | SGR |
| NCS-A | Prod/Monitor | NAVFACMAR |
| NCS-B1 | Production | NAVFACMAR |
| NCS-9A | Production | NAVFACMAR |
| NCS-10 | Production | NAVFACMAR |
| **Hagåtña Basin** | | |
| A-1 | Production | GWA |
| A-2 | Production | GWA |
| A-3 | Production | GWA |
| A-4 | Production | GWA |
| A-5 | Production | GWA |
| A-6 | Production | GWA |
| A-7 | Production | GWA |
| A-8 | Production | GWA |
| A-9 | Production | GWA |
| A-10 | Production | GWA |
| A-12 | Production | GWA |
| A-13 | Production | GWA |
| A-14 | Production | GWA |
| A-15 | Production | GWA |
| A-16 | Monitoring | CWMP |
| A-17 | Production | GWA |
| A-18 | Production | GWA |
| A-19 | Production | GWA |
| A-20 | Monitoring | CWMP |
| A-21 | Production | GWA |
| A-23 | Production | GWA |
| **Hagåtña Basin** | | |
| A-25 | Production | GWA |
| A-26 | Production | GWA |
| A-28 | Production | GWA |
| A-29 | Production | GWA |
| A-30 | Production | GWA |
| A-31 | Production | GWA |
| A-32 | Production | GWA |
| BPM-1 | Monitoring | CWMP |
| EX-1 | Monitoring | CWMP |
| EX-4 | Monitoring | CWMP |
| EX-9 | Monitoring | CWMP |
| NAS-1 | Production | GWA |
| NRMC-1 | Production | NAVFACMAR |
| NRMC-2 | Production | NAVFACMAR |
| NRMC-3 | Production | NAVFACMAR |
| **Mangilao Basin** | | |
| AECOM-10 | Test Boring | NAVFACMAR |
| AECOM-11 | Test Boring | NAVFACMAR |
| EX-11 | Production | GWA |
| HRP-1 | Industrial | HRP |
| HRP-2 | Industrial | HRP |
| M-1 | Production | GWA |
| M-2 | Production | GWA |
| M-3 | Production | GWA |
| M-4 | Production | GWA |
| M-8 | Production | GWA |
| M-9 | Production | GWA |
| M-23 | Production | GWA |
| MGC-1 | Irrigation | MGC |
| MGC-2 | Irrigation | MGC |
| MGC-3 | Irrigation | MGC |
| MGC-4 | Irrigation | MGC |
| NCS-3A | Production | NAVFACMAR |
| NCS-8 | Production | NAVFACMAR |
| **Yigo-Tumon Basin** | | |
| AECOM-8 | Test Boring | NAVFACMAR |
| AECOM-9 | Monitoring | NAVFACMAR |
| AFMW-1 | Production | NAVFACMAR |
| AFMW-2 | Production | NAVFACMAR |
| AFMW-3 | Production | NAVFACMAR |
| AFMW-5A | Production | NAVFACMAR |
| AFMW-6 | Production | NAVFACMAR |
| AFMW-7 | Production | NAVFACMAR |
| AFMW-8A | Production | NAVFACMAR |
| AFMW-9A | Production | NAVFACMAR |
| D-1 | Production | GWA |
| D-2 | Production | GWA |
| D-3 | Production | GWA |
| D-4 | Production | GWA |
| D-5 | Production | GWA |
| D-6 | Production | GWA |
| D-7 | Production | GWA |
| D-8 | Production | GWA |
| D-9 | Production | GWA |
| D-10 | Production | GWA |
| D-11 | Production | GWA |
| D-12 | Production | GWA |
| D-13 | Production | GWA |
| D-14 | Production | GWA |
| D-15 | Production | GWA |
| D-16 | Production | GWA |
| **Yigo-Tumon Basin** | | |
| D-17 | Production | GWA |
| D-18 | Production | GWA |
| D-19 | Production | GWA |
| D-20 | Production | GWA |
| D-21 | Production | GWA |
| D-25 | Production | GWA |
| D-26 | Production | GWA |
| D-27 | Production | GWA |
| D-28 | Production | GWA |
| EX-5A | Production | GWA |
| EX-6 | Monitoring | CWMP |
| EX-7 | Monitoring | CWMP |
| EX-10 | Monitoring | CWMP |
| F-5 | Production | GWA |
| F-6 | Production | GWA |
| F-7 | Production | GWA |
| F-9 | Production | GWA |
| F-19 | Production | GWA |
| F-20 | Production | GWA |
| FM-1A | Production | Foremost |
| GH-501 | Production | GWA |
| GHURA-DEDEDO | Monitoring | CWMP |
| GPH-1 | Production | GPH |
| GPH-2 | Production | GPH |
| H-1 | Production | GWA |
| M-5 | Production | GWA |
| M-6 | Production | GWA |
| M-7 | Production | GWA |
| M-10A | Monitoring | CWMP |
| M-11 | Monitoring | CWMP |
| M-12 | Production | GWA |
| M-14 | Production | GWA |
| M-15 | Production | GWA |
| M-17A | Production | GWA |
| M-17B | Production | GWA |
| M-18 | Production | GWA |
| M-20A | Production | GWA |
| M-21 | Production | GWA |
| NCS-2A | Production | NAVFACMAR |
| NCS-5 | Production | NAVFACMAR |
| PBI-1 | Industrial | PBI |
| TMT-1 | Production | NAVFACMAR |
| Y-1 | Production | GWA |
| Y-2 | Production | GWA |
| Y-3 | Production | GWA |
| Y-4A | Production | GWA |
| Y-5 | Production | GWA |
| Y-6 | Production | GWA |
| Y-7 | Production | GWA |
| Y-9 | Production | GWA |
| Y-10 | Production | GWA |
| Y-12 | Production | GWA |
| Y-14 | Production | GWA |
| Y-16 | Production | GWA |
| Y-17 | Production | GWA |
| Y-18 | Production | GWA |
| Y-19 | Production | GWA |
| Y-20 | Production | GWA |
| Y-21A | Production | GWA |
| Y-22 | Production | GWA |
| Y-23 | Production | GWA |

NOTES:
GWA - Guam Waterworks Authority
NAVFACMAR - Naval Facilities Engineering Command Marianas
CWMP - Comprehensive Water Monitoring Program
SGR - Starts Golf Resort
HRP - Hawaiian Rock Products
GPH - Guam Plaza Hotel
MGC - Mangilao Golf Course
PBI - Perez Bros. Inc.

Deep monitoring wells, designated as EX wells were installed during the Northern Guam Lens Study between 1981 and 1982. Monitoring wells EX-1, EX-4, EX-6, EX-8, EX-9, EX-10, and GHURA-DEDEDO were rehabilitated in 2000. Other current monitoring wells, which track water table elevations (A-16, A-20, MW-10A and MW-11), were originally constructed as production wells, but were taken out of production due to elevated chloride concentrations or poor performance. In 2010, AECOM Technical Services installed 11 test borings (AECOM-1 through AECOM-11) in northern Guam for NAVFACMAR. Two (AECOM-3 and AECOM-9) were designed to be monitoring wells (AECOM 2011).

## 1.4 Groundwater Salinity

### Definitions and Measurement Concepts: Salinity, Chloride Concentration, and Specific Conductance (Conductivity)

Salinity is defined as the total mass of solutes in water, including dissolved gases but excluding dissolved organic substances (Trujillo and Thurman 2011). It is expressed as a ratio of the dissolved mass to the water mass, in terms of parts per thousand (ppt or ‰). Seawater salinity across the globe ranges between 33‰ to 38‰ (Trujillo and Thurman 2011). In the vicinity of Guam, seawater salinity is 34‰, at the low end of the global range, by virtue of its location in the humid tropics. The major solutes in seawater are chloride, sodium, sulfate, magnesium, calcium, and potassium (Appendix A). The chloride ion accounts for over 55% of the total weight of dissolved solids and is the easiest solute to measure accurately (Trujillo and Thurman 2011). Chloride concentration is thus the customary index of groundwater salinity, and is generally reported in milligrams per liter (mg/l). The U.S. EPA *National Secondary Drinking Water Regulations* lists the secondary (non-enforceable) standard for chloride as 250 mg/l. Chloride concentration can be measured directly by laboratory titration or by chloride-specific electronic probes in the laboratory or field. For seawater and dilutions of seawater with pure freshwater the standard relationship is

$$S\,‰ = 1.80655\times10^{-3}\,‰\cdot {}^{l}\!/_{mg}\left[\mathrm{Cl}^{-}\right]$$

where $S$ is salinity and $[Cl^-]$ is chloride concentration in mg/l (Lewis 1980).

Specific conductance is the conductivity of an electrolytic solution normalized to the standard temperature of 25°C. Conductivity is a measure of how efficiently a material can conduct electricity. Conductivity measurements of aqueous solutions do not distinguish different types of ions but indicate the combined effect of all the ions present in the water (Aquarius Technologies 2002). The unit of specific conductance of water is microsiemens per centimeter (μS/cm).[2] Conductivity of high quality deionized water is about 5.5 μS/cm. Conductivity of typical drinking water is three to four orders of magnitude higher, ranging from about 5 to 50 mS/m. Seawater conductivity is another three orders of magnitude higher, at about 5 S/m. Seawater's conductivity is thus about a million times higher than that of deionized water, and a hundred to a thousand times higher than that of typical drinking water (*Wikipedia*: Conductivity (electrolytic)).

Table 2 summarizes salinity, chloride, specific conductance, and density ranges found in various natural waters, which have been compiled from various sources. Table 3 provides

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[2] *Siemens* and *mho* are equivalent terms: Although *siemens* is the SI term for conductance, and is used broadly in scientific and often in electrical applications, *mho* is commonly seen in older literature and is still used in electronic applications, such as instruments for measuring conductivity (*Wikipedia*: Siemens (unit)).

a rating table for comparisons of specific conductance to salinity from 100-65,000 μS/m (Wagner et al. 2006; Miller et al. 1988).

**Table 2**: Summary of general salinity, chloride, specific conductance, and density ranges found in natural waters (USEPA, 2016; World Health Organization, 2011).

| Water Quality | Salinity | | | Chloride | Specific Conductance | Density |
|---|---|---|---|---|---|---|
| | % | ‰, ppt | ppm | mg/l | μS/cm | kg/m³ |
| Fresh water | < 0.05 | < 0.5 | < 500 | > 1 - 250 | 1 - 1,500 | 996 - 1,000 |
| USEPA secondary standard | | | | 250 | | |
| WHO guideline | | | | None | | |
| Brackish water | 0.05 - 3 | 0.5 - 30 | 500 - 30,000 | 250 - 19,000 | 1,500 - 46,000 | 1,000 - 1,024 |
| Sea water (global average) | 3.5 | 35 | 35,000 | 19,000 | 54,000 | 1,024 - 1,028 |
| Saline water | 3 - 5 | 30 - 50 | 30,000 - 50,000 | 19,000 - 45,000 | 46,000 - 70,000 | 1,024 - 1,030 |
| Brine water | > 5 | > 50 | > 50,000 | >45,000 | > 70,000 | > 1,030 |

**Table 3**: Rating table for conversion of specific conductance to salinity. Specific conductance in units of μS/cm can be converted to salinity in units of parts per thousand for measurements at atmospheric pressure (Wagner et al. 2006; Miller et al. 1988).

| Specific conductance (μS/cm) | Salinity (‰) | Specific conductance (μS/cm) | Salinity (‰) |
|---|---|---|---|
| 100 | 0.040 | 23,000 | 13.878 |
| 300 | 0.131 | 26,000 | 15.872 |
| 500 | 0.226 | 29,000 | 17.895 |
| 700 | 0.324 | 32,000 | 19.945 |
| 1,000 | 0.474 | 35,000 | 22.022 |
| 2,000 | 0.997 | 38,000 | 24.124 |
| 3,800 | 1.984 | 41,000 | 26.252 |
| 5,000 | 2.664 | 44,000 | 28.405 |
| 7,000 | 3.826 | 47,000 | 30.582 |
| 9,000 | 5.016 | 50,000 | 32.783 |
| 11,000 | 6.229 | 53,000 | 35.008 |
| 13,000 | 7.463 | 56,000 | 37.257 |
| 15,000 | 8.714 | 59,000 | 39.530 |
| 17,000 | 9.983 | 62,000 | 41.826 |
| 20,000 | 11.914 | 65,000 | 44.146 |

### Processes Affecting NGLA Salinity

Seawater is the primary source of salt in the NGLA. Surface seawater salinity varies around the globe, however, mainly as a function of systematic latitudinal variations in evaporation and rainfall (Trujillo and Thurman 2011). Groundwater salinity is also affected by the salinity of the rainfall. Sea spray collected on the vegetation and ground, and mobilized by infiltrating water, is another source of salt affecting the NGLA. Sea spray salt is deposited onto the land surface and infiltrates into the groundwater during subsequent rainfall events, whether through diffuse flow or fast flow. Johnson (2012) found atmospheric deposition of chloride to be seasonally and spatially variable on the northern Guam plateau;

cumulative concentrations in rainwater collected at three stations sampled during five consecutive 3-to-5-month measurement periods between March 2010 and January 2011—the Guam International Airport, Beng Bing in Yigo, and well Y-15 near the back gate of Anderson Air Force Base—ranged from a minimum of 1.86 mg/l at Y-15 to a maximum of 14.8 mg/l at the airport.

Dissolution of the limestone by freshwater contributes calcium and magnesium to Guam's groundwater, thus increasing its hardness.[3] Seawater is about 1.3‰ magnesium ion and 0.42‰ calcium ion by weight, so that to the extent it is present it also contributes to the hardness of the water. The hardness of untreated groundwater on Guam is between 172 and 610 ppm $CaCO_3$ (Guam Waterworks Authority 2010), which rates as hard to very hard groundwater.

Manmade sources of salt affecting groundwater salinity can include agriculture, industrial waste, septic systems, water softeners, and leakage of chlorine-treated potable water from distribution pipelines.

**Freshwater-Saltwater Interface**

The density of freshwater is about 1,000 kilograms per cubic meter (kg/m$^3$) and the density of seawater is roughly 1,025 kg/m$^3$. This density difference, which is temperature dependent, allows freshwater to float on top of seawater. The (static) Ghyben-Herzberg principle (or simply Archimedes Law) notes that given a density difference of 1/40, for every unit of freshwater above sea level in an unconfined aquifer, there are 40 feet of freshwater in the water column below sea level (Figure 4). In the Ghyben-Herzberg equation, below, $\rho_f$ is the density of freshwater; $\rho_s$ is the density of seawater; $h$, hydraulic head, is the elevation of freshwater above sea level, and $z$ is the depth to the freshwater-saltwater interface.

$$z = \frac{\rho_f}{(\rho_s - \rho_f)} h$$

The Ghyben-Herzberg model assumes a sharp interface at the bottom of the freshwater lens, but more realistically can be applied to the mid-level of the mixing zone (Mink 1976). The mid-level of the mixing zone is where groundwater salinity is 50% freshwater and 50% seawater, and is thus marked by the 50% seawater isochlor. It should be noted that contrary to the simplifying assumption of a static body of freshwater, which is inherent in the Ghyben-Herzberg model, the lens is actually dynamic, which causes a deepening of the freshwater and mixing with underlying seawater (Mink 1976). According to Underwood et al. (1992), the mixing of freshwater and saltwater is primarily a result of tidal fluctuations, and to a lesser extent via dispersion processes (Shalev et al. 2009). The rising and falling of ocean tides continually push and pull the freshwater-saltwater interface first landward and then seaward during each tidal cycle (Barlow 2003). The 50% seawater isochlor is more reliable indicator of the volume of water in the freshwater lens than the water table (hydraulic head) because it reflects long-term conditions rather than the kinds of short-term, or near-instantaneous, perturbations that can affect the water table, such as pumping and variable recharge (CDM 1982b).

[3] Hardness is a property of water causing formation of insoluble residue with soap or scale in vessels from which water has evaporated. It is primarily due to ions of magnesium and calcium, but also other alkali metal and other metal ions. It is generally expressed, however, as mg/l or ppm of $CaCO_3$ (Neuendorf et al. 2011).

### Saltwater Encroachment and Intrusion

In coastal aquifers, the dynamic freshwater lens displaces the underlying saltwater over which it flows (Barlow 2003). When groundwater is extracted from it (Figure 4), however, the amount of freshwater in storage decreases, and so does the volume rate of flow to the coast, thus drawing the freshwater-saltwater interface inland and upward. The lateral inland incursion of saltwater within the aquifer is termed *saltwater encroachment.* The vertical upward adjustment of saltwater in the aquifer is termed *saltwater intrusion* (Kumar 2006). *Saltwater up-coning* is a specific type of intrusion, in which saltwater beneath an extraction well moves upward as pumping decreases pressure head within the well (Kumar 2006).

Encroachment and intrusion can result from either natural or artificial causes. Natural factors include changes in recharge or discharge, and the geologic structure and hydraulic properties of the aquifer, including the presence or absence of confining units within the aquifer (Kumar 2006). Artificial controls that determine the severity of saltwater encroachment and intrusion include the rate and volume of groundwater extracted, and depths and spacing of wells. Lateral and vertical movement of saltwater within the NGLA are complicated by its heterogeneous triple-porosity karst system, so that simple concepts of up-coning and uniform movement of the saltwater-freshwater interface, as shown in textbook schematic diagrams, such as Figure 4, do not strictly apply.

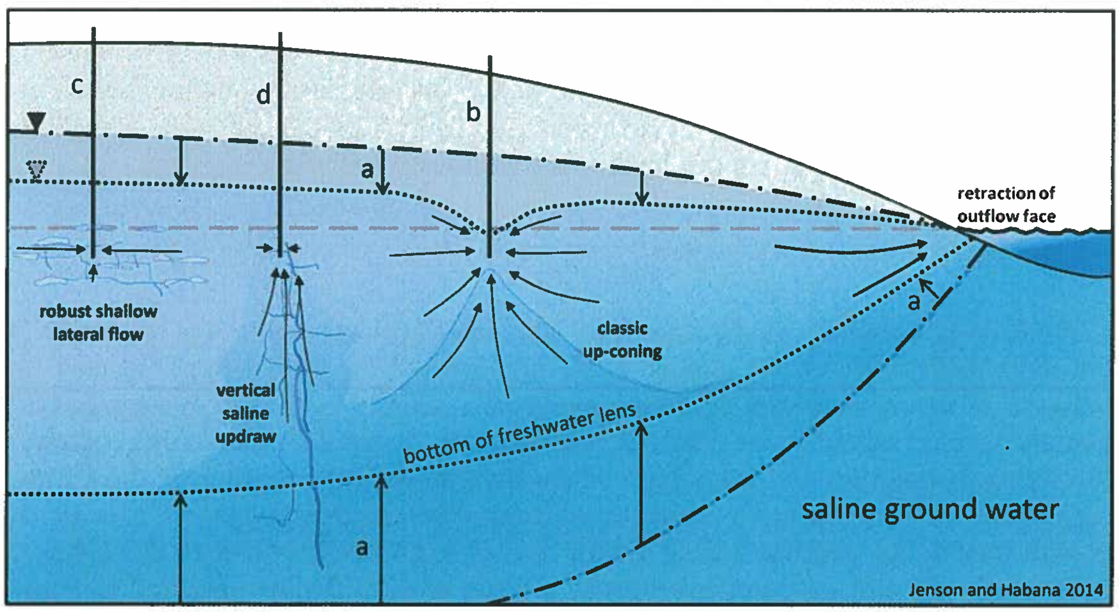


**Figure 4**: The general response of the freshwater lens to artificial withdrawal, and/or natural decrease in recharge, is shoreward retraction of the coastal outflow face and overall thinning of the freshwater lens. a) Thinning of the lens and retraction of outflow face. b) Classic simplistic model of response to extraction from a uniformly porous matrix of modest hydraulic conductivity. Significant drawdown induces upconing of more saline waters at the base of the lens. c) In island karst aquifers, sites with enhanced lateral conductivity at and just below the water table are less responsive to intrusion. Water-table drawdown is negligible and basal up-draw of saltwater are negligible. d) At sites that contact vertical pathways, such as solution-enhanced fractures, saltwater intrusion is exacerbated so that even shallow, low-capacity wells are at risk. Although drawdown may be negligible, there is substantial up-draw of brackish water or saltwater from below.

## 2 PREVIOUS SALINITY STUDIES ON GUAM

### 2.1 Groundwater Resources on Guam (Mink 1976)

In his 1976 report prepared for PUAG, subsequently published as WERI Technical Report No. 1, Mink provided the first comprehensive evaluation of past, present, and future groundwater development on Guam. Prior to the successful groundwater extraction program initiated in the mid-1960's using vertical wells, the predominant sources of potable water on Guam were spring water and impounded surface water (Fena Reservoir). Other successful sources of potable water built prior to 1965 include the Tumon-"Maui" horizontal shaft, three vertical military wells installed in the MARBO area, and private wells FM-1, H-1, and HRP-1. Most wells drilled prior to the 1960's were probably set deeper than necessary and almost certainly over-pumped, resulting in high salinity and eventual abandonment.

In this initial study, Mink proposed the following chloride concentration benchmarks for evaluating and managing groundwater quality within the NGLA:

- Background: 15 to 20 mg/l chloride
- Para-basal: Less than 20 mg/l chloride (i.e., background)
- Basal: 20 to 60 mg/l chloride (i.e., background to slightly higher)

The background chloride concentration accounts for chloride from rainfall and sea spray. Mink advised that the portion of the freshwater lens within 2,000 feet of the ocean should be considered a *zone of mixture*, likely containing greater than 250 mg/l of chloride (the USEPA secondary standard).

Mink evaluated the chloride concentrations obtained from the 57 A-, D-, F-, M-, Y-and Miscellaneous-series production wells that existed at the time. Anomalously high chloride concentrations were noted in several basal wells, which Mink attributed to variable vertical and horizontal permeability throughout the aquifer, as well as improper well depth, construction, and pump rates. No increases in chloride concentrations were noted in the existing para-basal wells.

Mink noted that PUAG and the drillers were conscious of keeping the vertical wells shallow to avoid saltwater intrusion when the drilling program was initiated in 1964. His recommended well bottom depth was 25 feet below sea level, but could be extended to 35 feet and even 50 feet below sea level in order to achieve a 200 gallon per minute (gpm) production rate. Wells drilled after 1969 were commonly drilled to 50 or more feet below sea level. Table 4 presents Mink's 1976 recommended guidelines for future well depths and pumping rates.

**Table 4**: Mink's 1976 production well design guidelines.

| Bedrock Type | Hydraulic Conductivity (ft/d) | Hydraulic Head (ft) | Maximum Pump Rate (gpm) | Maximum Depth (ft bmsl) |
|---|---|---|---|---|
| Clean Limestone | 190 | 4 | 425 | 40 |
| Probable Limestone | 120 | 4 | 325 | 30 |
| Argillaceous Limestone | 52 | 4 | 140 | 25 |

Notes
ft/d - feet per day
ft - feet
gpm - gallons per minute
ft bmsl - feet below mean sea level

## 2.2 Northern Guam Lens Study (CDM and Mink 1982)

The 1982 Northern Guam Lens Study (NGLS) prepared by Camp Dresser and McKee, Inc. (CDM) and directed by John Mink is still the most comprehensive groundwater study conducted on Guam. The NGLS included drilling, geophysical, lithologic, and modeling studies to characterize aquifer properties and provide a basis for recommendations for exploration, well construction, and aquifer management. The report came in three parts: the Summary Report, Aquifer Yield Report, and Well Construction Manual.

Among the most important products of the NGLS was the first volcanic basement contour map defining the lower boundary of the aquifer. The basement contours were created primarily from lithologic data from well logs and seismic refraction data from a systematic survey of the areas open to civilian development. (The field study did not include military lands.) Using the new map, the NGLS demarcated six basins (termed "sub-basins" at the time), which were divided into 47 management zones. Additionally, a 4,000-foot coastal buffer zone is established, which was an extension of Mink's 2,000-foot coastal zone of mixture. This buffer zone extends inland along an identified saltwater encroachment area from Hagåtña Bay toward Mt. Barrigada.

Exploratory monitoring wells EX-1 through EX-11 were drilled across northern Guam into the freshwater and saltwater portions of the aquifer. Four of the deep monitoring wells (EX-1, EX-2, EX-3 and EX-11) were drilled to the volcanic basement contact. The EX wells were left uncased except within the Hagåtña Argillaceous Limestone. Using a conductivity probe at the EX wells, the thickness of the transition zone from freshwater to saltwater was found to be variable over the NGLA. The NGLS noted that lower permeability areas of the aquifer have thicker transition zones, and high permeability areas of the aquifer have thinner transition zones. At EX-4, located in the Hagåtña Argillaceous limestone, hydraulic conductivity was about 1,300 ft/d and the transition zone thickness was 80 feet, while at EX-10 in the cleaner limestone, hydraulic conductivity was about 6,600 ft/d and the transition zone thickness was 32 feet. Specific conductance measurements collected across the NGLA were reported to range from 300 to 1,300 microsiemens/cm. Higher measurements of specific conductance were attributed to higher chloride concentrations associated with nearby saltwater.

The NGLS noted that chloride content is the most useful index of saltwater intrusion and revised the chloride concentration benchmarks (from the Mink 1976 report) for groundwater quality within the NGLA:

- Para-basal: Less than 30 mg/l chloride
- Saltwater toe: 30 to 70 mg/l chloride
- Basal: 70 to 150 mg/l chloride (in which 150 mg/l was the design standard maximum for wells in the basal zone)
- Saltwater up-coning: Greater than 150 mg/l chloride

The NGLS states that wells in most areas of the NGLA had operated successfully and had not experienced serious or widespread degradation of groundwater quality as a result of saltwater up-coning. Elevated chloride wells were situated in the Andersen Basin and northwest portion of the Hagåtña Basin. In the Andersen Basin, all wells except BPM-1 were abandoned due to high chloride concentrations. Table 5 summarizes the chloride and conductivity trends documented in Table 6-1 in the NGLS Aquifer Yield Report.

**Table 5**: Summary of chloride and conductivity trends documented in the NGLS (Table 6-1, Aquifer Yield Report).

| Sub-basin | Water Quality Trends | |
|---|---|---|
| | Chlorides (mg/l) | Conductivity (µmhos/cm) |
| Hagatña | Initially at 15<br>Early wells increased slightly to and steady at 20-40<br>Later wells from 75 to 250-300 | Steady at about 500 for earlier wells<br>900-1,300 for some later wells |
| Yigo-Tumon | Initially at 15-20<br>Most steady at about 50<br>D-8, D-9 and D-13 rose to 200-400<br>Y-series wells rose from 20-40 and steady | Steady at 400-600 |
| Finegayan | Initially at 20<br>Steady between 50 and 150 | Steady at 500-800 |
| Agafa Gumas | Initially at 13<br>Steady between 15 and 40 | Steady at 450 |
| Andersen | Generally elevated to 400 | BPM-1 steady at 600<br>Older wells at 1,000-2,000 |
| Mangilao | Initially at 20-30<br>Generally steady at 30-50<br>M-1 at 150-250 mg/l | Most steady at 400-500<br>M-1 and M-9 at 800-1,000 |

Table 6 summarizes the 1982 NGLS production well design guidelines. Although not explicit in Table 6, the NGLS advised that aquifer permeability strongly determines production well capacity; the lower the aquifer permeability, the lower the production capacity should be.

**Table 6**: NGLS production well design guidelines.

| Groundwater Type | Region/Zone | Hydraulic head (feet) | Maximum Pump Rate (gpm) | Preferred depth (ft bmsl) | Maximum Depth (ft bmsl) |
|---|---|---|---|---|---|
| Basal | All basal areas | Less than 4 | 200 | 25 | 40 |
| | | Greater than 4 | 350 | 35 | 50 |
| Para-basal | Southern Hagatña sub-basin | NA | 200 (350*) | NA | 50 |
| | Upper Yigo sub-basin | NA | 750 | NA | 50-60 |
| | Other para-basal areas | NA | 500 | NA | 50 |

Notes:
Production wells should not be placed within 500 feet of saltwater toe position in clean limestone.
Production wells should not be placed within 1,000 feet of saltwater toe position in argillaceous limestone.
Minimum distance between production wells is 300 feet.
gpm - gallons per minute
ft bmsl - feet below mean sea level
* Higher pump rate of 350 gpm allowed under special considerations.

## 2.3 Historical Water Quality of PUAG Production Wells (Clayshulte 1985)

Clayshulte's 1985 study, prepared for the Guam Environmental Protection Agency (Guam EPA) and published as WERI Technical Report No. 57, evaluated groundwater quality data obtained from PUAG production wells between late 1976 and December 1983. Clayshulte tabulated and evaluated PUAG groundwater quality data using statistical, regression, and cluster analyses. Water quality parameters included temperature, pH, specific electrical conductance, turbidity, color, taste, total hardness, calcium hardness, total alkalinity, total coliform bacteria, and chloride concentration.

Clayshulte noted that both low and high quality wells exist in both basal and para-basal groundwater areas. Higher chloride concentrations attributed to saltwater intrusion were identified in the basal groundwater zone of the Hagåtña Argillaceous Limestone. Referencing the management zones established in the NGLS, Clayshulte identified specific management zones that should be avoided due to poor groundwater quality, and low priority areas with moderate to poor groundwater quality; all of these zones are in basal groundwater areas. Three types of chloride behavior trends were determined: positive/increasing, negative/decreasing, and cyclic (Table 7). The GHURA well is currently referred to as production well GH-501.

**Table 7**: Clayshulte's chloride behavior trends.

| Well series | Positive trend | Cyclic trend | Negative trend |
|---|---|---|---|
| A | A-9, A-13 | A-10, A-19 | None |
| AG | AG-1 | None | None |
| D | D-14, D-16, GHURA | D-11, D-17 | D-6, D-7, D-10, D-18 |
| F | F-7, F-8 | F-5, F-6 | F-9, F-10, F-11 |
| M | M-1, M-6 | M-9, M-12, M-14 | M-2, M-3 |
| Y | Y-1, Y-2, Y-4 | None | None |

## 2.4 Groundwater in Northern Guam: Sustainable Yield and Ground Water Development (BCG and Mink 1992)

This report prepared for Barrett Consulting Group (BCG) by John Mink focuses mainly on sustainable yield concerns within the NGLA, but discusses groundwater salinity data collected since the 1982 NGLS. The report presents salinity-depth curves from deep monitoring wells EX-1, EX-4, EX-6, EX-7, EX-8, EX-9, EX-10, and GHURA-DEDEDO. At these monitoring wells, the base of the lens (50% seawater isochlor) remained relatively stable between 1982 and 1989, even at EX-1 and EX-4, located in the lower permeability Hagåtña Argillaceous Limestone. This report concluded that the rate of groundwater extraction had not significantly affected the volume of freshwater within the lens. The report suggested revised production capacities based on performance histories of operational production wells on Guam and Hawaii (Table 8).

**Table 8**: BCG and Mink 1992 production capacity guidelines.

| Bedrock Type | Groundwater Zone | Hydraulic head (feet) | Well Capacity (gpm) |
|---|---|---|---|
| Clean limestone | Basal | 3 - 4 | 180 - 300 |
| | Basal | 2 - 3 | 80 - 150 |
| | Para-basal | > 4 | 500 - 700 |
| Argillaceous limestone | Basal | > 5 | 150 - 200 |
| | Basal | 3 - 5 | < 150 |
| | Para-basal | > 7 | 200 - 300 |

Note:
gpm - gallons per minute

### 2.5 Nutrient Flux Study (Matson 1993)

In this journal article, *Nutrient flux through soils and aquifers to the coastal zone of Guam (Mariana Islands)*, Matson evaluated the nutrient chemistry of soils, well water, and coastal discharge waters around northern Guam. Notably, chloride analysis was conducted for two years (1987-1989) at Tumon Bay and Tarague beach seeps, and at three private, variable-depth, Fadian Fish Hatchery wells. In the Fadian wells, salinity was 34-35‰ at the seawater well, 17-18‰ at the brackish well, and 3.2‰ at the freshwater well. Chloride concentrations were most variable within the brackish well, which Matson attributed to its location within the transition zone. Matson noted that chloride concentrations in beach seeps fluctuated quickly in response to heavy short-term rainfall events, and varied seasonally, such that chloride concentrations were highest in the dry season and lowest in the wet season. Chloride concentrations were routinely lower in beach seeps at Tarague along the northern coast than at Tumon Bay along the western coast. The average salinity of both beach seeps was 3.14‰, comparable to the freshwater Fadian Fish Hatchery well.

### 2.6 Chloride History and Trends of Water Production Wells in the Northern Guam Lens Aquifer (McDonald and Jenson 2003)

WERI Technical Report No. 98 (McDonald & Jenson, 2003) assesses the incidence of chloride contamination in 128 PUAG/GWA, and Navy production wells between 1973 and 1999, identifies probable causes of elevated chloride concentrations, and provides risk management guidelines to address the chloride contamination. This study utilized the 1982 NGLS chloride concentration benchmarks and introduced the Safe Drinking Water (SDW) guideline of 250 mg/l established by the U.S. Environmental Protection Agency and recommended by the World Health Organization (Table 2).

Linear regression of chloride concentrations over time revealed significant increasing trends in 64 (50%) of the 128 production wells. Decadal average chloride concentrations (1970s, 1980s, and 1990s) and probable saltwater intrusion occurrences were discussed for each sub-basin. One of the focal points of the study was documentation of the construction (well depth and screen placement) and operation (pumping rate) histories of the wells that exhibited particularly high chloride concentrations. McDonald and Jenson categorized the production wells into three broad categories according to their performance histories:

1. Stayed within an original benchmark category
2. Increased sufficiently to cross into another benchmark category
3. Started and stayed high (i.e. above the saltwater up-coning or SDW category)

The report concluded with specific recommendations for each well based on the extant magnitude and trend in chloride concentration for each well.

## 3 DATA TYPES AND LIMITATIONS

### 3.1 Salinity Measurement Data

#### Chloride

This study utilizes chloride data collected from NGLA production wells between 1973 and 2010, which were provided by GWA, NAVFACMAR, Guam EPA, and WERI. The study builds upon the 2003 McDonald and Jenson report, with additional chloride data from 1999 through 2010, and the inclusion of Air Force and private freshwater production wells. Each production well sample represents the groundwater quality immediately surrounding the well during sample collection, from which groundwater enters the well at the pump intake depth across the screen interval. Untreated groundwater is collected from a sample port at the production well and sent to a laboratory for chloride analysis in accordance with approved USEPA methods.

Chloride sampling frequencies vary between agencies, and have changed over time. For PUAG/GWA production wells, chloride was sampled monthly from 1973 through 1983, but quarterly from 1984 through 2010. For Navy production wells, chloride sampling was weekly from 1995 through 1997, bi-weekly from 1998 through 2000, weekly from 2001 through 2004, and monthly from 2005 through 2009. For Air Force production wells, chloride sampling occurred quarterly from 1986 to 2010. For private freshwater production wells, chloride analysis occurred annually from 1987 to 2010, as documented in Guam EPA well inspections conducted each February. Data gaps exist to varying degrees throughout all of the well chloride datasets. Graphs depicting the chloride and production history at each production well are included in the *Northern Guam Lens Aquifer Database* (Bendixson et al., 2014) (Appendix F).

**Specific Conductance (Conductivity)**

Specific conductance profiles examined here were collected quarterly by the USGS from deep monitor wells from May 2005 through October 2010 as part of an ongoing data collection program. The deep monitor wells on Guam penetrate through the freshwater lens and into or through the transition zone. The specific conductance profiles are measurements of specific conductance relative to depth throughout the total depth of the well. To profile the wells, an instrument that records *conductivity, temperature, and depth* (CTD) data is lowered down each well using a stainless steel cable marked with known depths. Specific conductance is calculated using the conductivity measurements and the fluid temperatures within the well. Elevation is computed from pressure readings and referenced to the marks on the stainless steel cable by pausing the CTD at the cable marks.

The CTD, which was designed for oceanographic work, is most accurate in pure seawater, and its accuracy decreases in brackish to freshwater. The CTD is therefore checked against standards prior to measuring the profiles. Temperature checks are also performed between 10°C and 30°C.[4] Specific conductance standards of 500, 1,000, 2,500, 5,000, 10,000, 25,000, and 50,000 µS/cm are used to span nearly the entire range of specific conductance found in the wells. The mean error for the specific conductance standards is as follows:

| Standard (µS/cm) | Mean Error (%) |
|---|---|
| 500 | 14.9 |
| 1,000 | 8.2 |
| 2,500 | 5.0 |
| 5,000 | 7.9 |
| 10,000 | 3.3 |
| 25,000 | 2.7 |
| 50,000 | 2.4 |

[4] Basic compensation is normally done by assuming a linear increase of conductivity versus temperature of typically 2% per degree (*Wikipedia*: Conductivity (electrolytic)).

**Correlation of Chloride and Conductivity in NGLA Production Wells**

Utilizing 3,800 groundwater quality samples collected from GWA production wells from 2001 through 2011, chloride and conductivity results were correlated to determine a conductivity value equivalent to the 250 mg/l chloride benchmark and specific to NGLA groundwater (Figure 5). The following formula for chloride as a function of conductivity is obtained from the regression:

$$\left[\mathrm{Cl}^-\right] = 0.3283\,\tfrac{\mathrm{mg \cdot cm}}{\mu\mathrm{S \cdot l}} \cdot \kappa - 107.46\,\tfrac{\mathrm{mg}}{\mathrm{l}}$$

where $[Cl^-]$ is chloride ion concentration in milligrams per liter (mg/l) and $\kappa$ is conductivity in microsiemens (or micromhos) per centimeter (µS/cm) at ~27° C. (Chloride-conductivity data were not normalized to standard temperature, but plotted as measured in the field, at temperatures which are mostly within a degree or two of 27° C.) The correlation identified 1,100 µS/cm specific conductance as equivalent to 250 mg/l chloride for the NGLA.

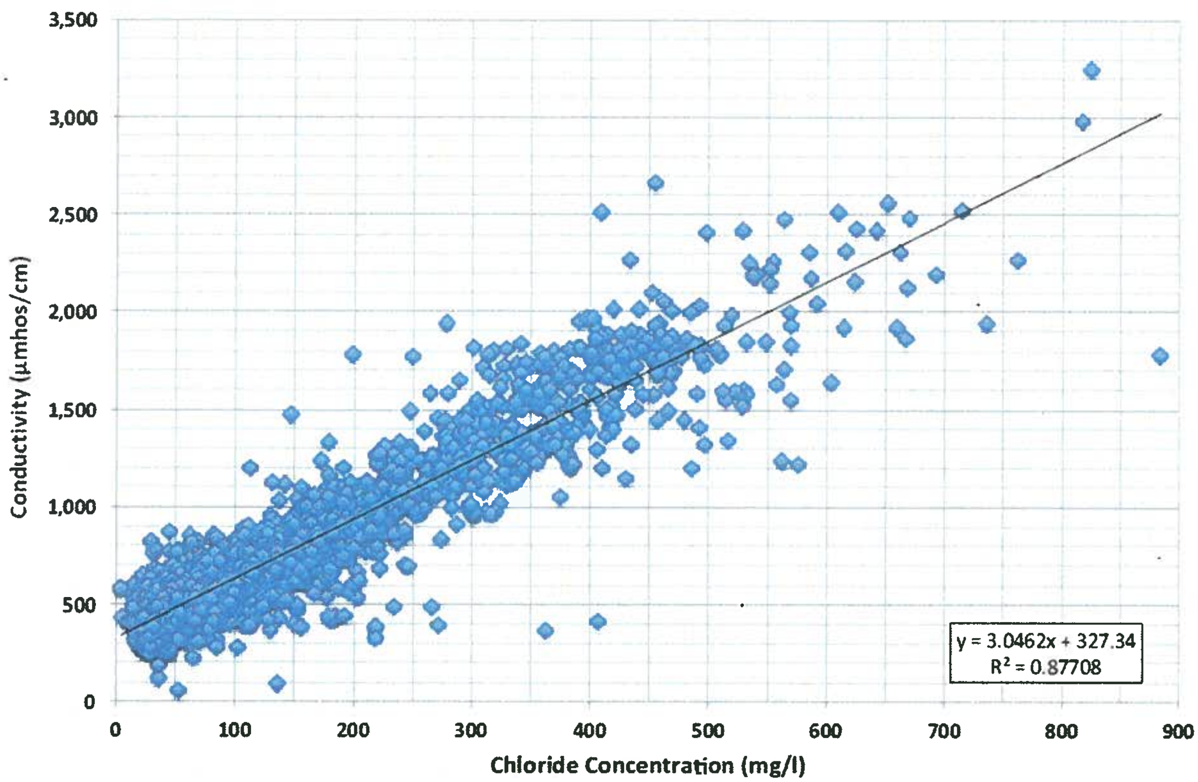


**Figure 5**: Correlation of chloride and conductivity data from 3,800 NGLA groundwater samples collected from GWA production wells from 2001 through 2011. Approximately 80% of all groundwater samples lie within the domain ≤250 mg/l chloride concentration (and thus the range ≤1,100 µS/cm (µmhos/cm) specific conductance).

## 3.2 Aquifer Management Data

### Well Construction and Depth

Data on well construction and depth are obtained from the *Northern Guam Lens Aquifer Database* (Bendixson et al. 2014), which is maintained by WERI, and was utilized to provide pumping parameters for the numerical groundwater model constructed for the recent *Guam*

*Groundwater Availability Study* (Gingerich and Jenson 2010; Gingerich 2013). The database contains copies of drilling logs, well construction logs, well operation permits, and historical aquifer investigation reports shared by GWA, NAVFACMAR, and Guam EPA. As noted by Bendixson et al. (2014) many production and monitoring wells lack documentation regarding construction, depth, and screen intervals. Also as noted by Bendixson et al., available records contain discrepancies regarding the surveyed well-head elevations, which are used to calculate water-table elevations and well-bottom elevations. Bendixson et al. selected the most reliable calculations of water-table elevation and well-bottom depth based on their confidence in the data for surface topography, volcanic basement contours, and comparisons with nearby wells. They recommended field-checking and resurvey of sites at which such data were uncertain.

#### Production Rates/Volumes

Production data documented from 1980 through 2010 were obtained from GWA, NAVFACMAR, Guam EPA, and the 2003 McDonald and Jenson report. The production of groundwater from the aquifer is measured and reported either by rate in gallons per minute (gpm), million gallons per day (mgd), or million gallons per month. Production well operating permits, required by Guam EPA, stipulate that monthly production rates for each well be reported to Guam EPA on an annual basis. The well operating permit states the maximum volume that can be extracted each month, and lists the permitted pump rate that will comply with that maximum volume. GWA measures their production rates at each well in gpm on a daily basis. The rate of production at the NAVFACMAR and private freshwater production wells is unknown because the number of operational days for each well is not reported to Guam EPA or was not provided.

### 3.3 Hydrologic Data

#### Groundwater Levels

Water table elevations relative to mean sea level are commonly measured at monitoring wells using either a water-level probe (static groundwater levels), or using a pressure transducer placed within the well water column (continuous groundwater levels). For this study, the water-table elevations for each monitoring well were obtained from the National Water System web interface maintained by USGS (USGS 2011). The USGS reports both static groundwater levels and the daily average value for the continuous groundwater levels. Groundwater-level data have been collected by USGS at various monitoring wells from 1975 through 2010; however, no one monitoring well has been monitored continuously during this timeframe. Static water level measurements collected from test borings AECOM-1, AECOM-7, and AECOM-11, and monitoring wells AECOM-3 and AECOM-9, were also reviewed during this study.

#### Rainfall

Monthly rainfall data recorded at Andersen Air Force Base (AAFB) from 1953 through 2010 were obtained from the Global Historical Climatology Network – Monthly dataset provided by the National Climatic Data Center (NCDC 2011). The AAFB rainfall records were selected because of their longevity and minimal data gaps. Based upon a review of previous meteorological reports about Guam (Lander 1994; Lander and Guard 2003), the average annual rainfall at AAFB is a fair representation of the average annual rainfall distributed across northern Guam.

**Mean Sea Level**

Monthly MSL measurements recorded in feet at Apra Harbor from 1960 through 2010 were obtained from the National Oceanic and Atmospheric Administration (NOAA) historic tide database (NOAA 2011). The measurements are relative to the mean low low water (mllw) level, the average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch (NOAA 2011). The NOAA station is located at the western entrance to Sumay Cove Marina in outer Apra Harbor (Jenson and Jocson 1998). Data gaps that coincide with major storm events occurred during 1975, 1976, 1998, and 2004.

**Southern Oscillation Index**

Southern Oscillation Index (SOI) values from 1876 through 2010 were obtained from the Australian Bureau of Meteorology website (2011). The SOI is calculated from the monthly or seasonal fluctuations in atmospheric pressure differences across the Pacific Ocean between Tahiti and Darwin, Australia.

## 4 METHODS

### 4.1 Statistical Analysis of Chloride Data in Production Wells

Descriptive statistics and linear regression analyses of the reported chloride concentrations at each NGLA production well were conducted to evaluate temporal trends. Data compilation, time-series graphs, and linear regression calculations were done in Microsoft Excel. Apparent outliers were left in the chloride datasets because of the uncertainty of their origin in this complex aquifer. While some chloride concentrations are almost certainly artifacts of human or instrumental error, others may be indicative of actual aquifer processes. Because it is difficult to judge which is the case, we thus chose to leave apparently anomalous data points in each set, note their presence in the discussion, and consider their possible effects (and causes) in the interpretations.

Weekly chloride data sets reported from the Navy production wells were recast into monthly data sets to enable comparison with monthly production rates. For the Navy production wells, the highest weekly chloride concentration reported in any given month was selected as the monthly chloride concentration included in the time-series graphs of chloride and production.

Minimum, maximum, standard deviation, and decadal mean averages of the chloride concentrations were calculated for the intervals from 1973-1979, 1980-1989, 1990-1999, and 2000-2010 (Figures 6-9). Note that 2010 was incorporated into the mean decadal average for 2000-2009 to include the most recent available data. The decadal mean chloride concentrations for each production well were compared to the chloride benchmarks utilized by McDonald and Jenson (2003), with a revision of terminology, as shown in Table 9.

Although the benchmark values were retained, the proposed new descriptors were chosen to reflect groundwater quality and aquifer management considerations rather than implied associations with groundwater zones or the incidence of induced saltwater intrusion/encroachment, with which the respective values are only loosely correlated.

Linear regression was used to determine if the temporal trends exhibited by the chloride concentrations at the NGLA production wells were statistically significant. The calculated correlation coefficients [r] were compared to critical values of the correlation coefficient, [r(crit)], which were obtained from Table B.17 of *Biostatistical Analysis* (Zar 1999), according

**Table 9**: Chloride benchmark guidelines.

| McDonald and Jenson (2003) Chloride Benchmark | Proposed Chloride Benchmark Label | Chloride concentration (mg/l) | Color code for maps and spreadsheets |
|---|---|---|---|
| Para-basal | Exceptional | Less than 30 | Blue |
| Saltwater toe | Good | 30 to 70 | Green |
| Basal | Standard | 70 to 150 | Black |
| Saltwater up-coning | Marginal | 150 to 250 | Orange |
| SDW guideline | Out of standard | Greater than 250 | Red |

to a two-tailed test with a 95% confidence interval [alpha (α) of 0.05]. Calculated correlation coefficient values [r] qualified as significant if they exceeded the critical correlation coefficient values [r(crit)]. A linear regression data summary is provided in Appendix C.

## 4.2 Analysis of Chloride and Production Data

### Graphical Analysis of Chloride and Production Data

To visually evaluate the temporal relationships between chloride concentrations and production rates, scatterplot graphs of the two variables over time were created for each production well (Appendix F). For reasons discussed above, no outlier chloride concentrations were removed; anomalous or spurious data can be seen wherever they occur.

### Determining Well-Screen Lengths and Well Depths from the Historical Records

As described in Section 3.2, well depth and screen length at each production well were compiled from available drilling and other records contained in the *Northern Guam Lens Aquifer Database* (Bendixson *et al*., 2014). To assess whether well and screen depths might be contributing to salinity observed at any given well, the well depth and screen placement were compared to the NGLS production well design guidelines. Many production wells were installed in the 1960s and 1970s prior to the 1982 NGLS, of course, but the NGLS guidelines remain useful as benchmarks for evaluating well management. Estimated depths to the 250 mg/l and 50% seawater isochlor for the CWMP monitoring wells are given in Appendices D and F, respectively.

## 4.3 Analysis of Chloride Data with Hydrologic Variables

Using scatterplot graphs, chloride concentrations were compared with 1) monthly and annual rainfall data, 2) monthly MSL data, and 3) monthly SOI data over the past few decades for selected production wells representative of basal, para-basal, and supra-basal groundwater zones throughout the NGLA. (See Section 5.3.) The relationship between chloride concentrations within the groundwater zones and each hydrologic variable was evaluated subjectively based on the latest understanding of the NGLA.

## 4.4 Correlation of Chloride and Conductivity in Production Wells

Linear correlation was used to determine the relationship between conductivity measurements and chloride concentrations specific to the NGLA. Approximately 3,800 groundwater quality samples collected from GWA production wells between 2001 and 2011 and analyzed for chloride and conductivity were plotted on a scatterplot graph (Figure 5). According to GWA, their laboratory uses the same water sample to measure conductivity and chlorides according to approved U.S. EPA methods (Sian-Denton, personal communication); therefore, a direct correlation was possible. Through linear correlation a conductivity value equivalent to 250 mg/l chloride, the U.S. EPA National Secondary Drinking Water Regulation, was established specific to the NGLA.

## 4.5 Analysis of Specific Conductance Data in Monitoring Wells

The quarterly specific conductance measurements obtained by USGS from the deep monitoring wells were used to determine the lower limit of what we here call the *prime layer* (groundwater containing less than 250 mg/l chloride) as well as the lower limit of the freshwater lens, as defined by the depth to the 50% seawater isochlor. These depths were graphed to track how they fluctuated from 2005 through 2010. (See Section 5.4.)

### Prime Layer

For each salinity profile generated with specific conductance measurements, the elevation nearest the conductivity value equivalent to 250 mg/l chloride (i.e., 1100 µS/cm, Figure 5) was defined as the practical or "regulatory" bottom of the potable section of the freshwater lens (which can be defined as deeper, depending on one's salinity criterion for potability). Measured specific conductance values greater than 1100 µS/cm were considered brackish water to saltwater. The lower limit of the prime layer obtained using this methodology is approximate because specific conductance is normalized to 25°C but the GWA conductivity measurements were recorded at water temperatures of roughly 26-27°C. The freshwater lens elevations at each well, for all deep monitoring wells, were plotted over time in scatterplot graphs. (See Section 5.4 and Appendix D.)

### Freshwater-Saltwater Interface

For each salinity profile generated with specific conductance measurements, the elevation nearest to 27,000 µS/cm, half of the average specific conductance of seawater (54,000 µS/cm), was considered the freshwater-saltwater interface, or 50% seawater isochlor. The 50% seawater isochlor elevation at each well, for all deep monitoring wells, was plotted over time in scatterplot graphs. (See Section 5.4 and Appendix E.)

### Applying the Ghyben-Herzberg Principle to the NGLA

The 50% seawater isochlor depths obtained with specific-conductance data were compared to 50% seawater isochlor depths calculated by application of the Ghyben-Herzberg ratio to groundwater-head measurements. The Ghyben-Herzberg formula approximates the 50% seawater isochlor depth based on a 41:1 ratio of freshwater above MSL to freshwater below MSL. For this study, the ratio was applied to minimum, maximum, and mean of historical groundwater levels obtained from the deep monitoring wells between 1975 and 2010 to make first-order estimates of the respective 50% seawater isochlor depths. Independent observational data on salinity profiles within the aquifer are limited to profiles from seven deep monitoring wells maintained by the *Guam Comprehensive Water Monitoring Program* since 1998 (Appendix E) and previous deep monitoring wells installed during the 1982 NGLS (Jenson and Jocson 1998). Estimated depths to the 50% isochlor calculated from the modeling work done by the *Guam Groundwater Availability Study* (Gingerich 2013) can also be used comparison, and are shown on the basement map developed by Vann et al. (2014).

## 4.6 Well Field Cross-Sections

Interpretive cross-sections were constructed to aid in visualizing the depths and fluctuations of the freshwater lens thickness in three selected well fields: 1) Monitoring Well EX-10 situated northwesterly in the Yigo-Tumon Basin, 2) Monitoring Well GHURA-

DEDEDO situated centrally in the Yigo-Tumon Basin, and 3) Monitoring Well EX-4 situated southerly in the Hagåtña Basin. Volcanic basement contours and MSL from Vann et al. (2014) were included for reference. (See Section 5.5 and Figures 31-34.)

# 5 RESULTS AND DISCUSSION

## 5.1 Statistical Analysis of Chloride Data in Production Wells

Linear regression analysis of chloride concentrations revealed significant temporal trends at 112 of the 153 production wells (73%) within the NGLA (Appendix F). One-hundred-seven (107) production wells (70%) exhibited significant increasing trends. Five (5) production wells showed significant decreasing trends (NCS-A, NCS-B, NCS-5, NRMC-2, and MGC-4). Nine of the 10 private freshwater production wells (i.e., all except MGC-4) did not exhibit a significant temporal trend, which is attributed to low (annual) sample frequency and consistent sample period (each February). Fourteen (14) of 25 NAVFACMAR production wells (56%), and 18 of the 119 GWA production wells (15%) did not exhibit trends.

Descriptive statistics of the chloride concentrations included the minimum, maximum, standard deviation, and decadal mean averages from 1973-1979, 1980-1989, 1990-1999, and 2000-2010 (Figures 6-9). Since 1973, recorded chloride concentrations ranged from a minimum of 2.7 mg/l at para-basal production well A-3 to a maximum of 917.3 mg/l at basal production well D-13. In general, throughout the NGLA, chloride concentrations are more variable in recent decades compared to the 1970s. Chloride concentrations were higher during the 2000-10 decade than any of the previous decades in 112 of the 132 (84.8%) production wells with more than one decade of chloride data.

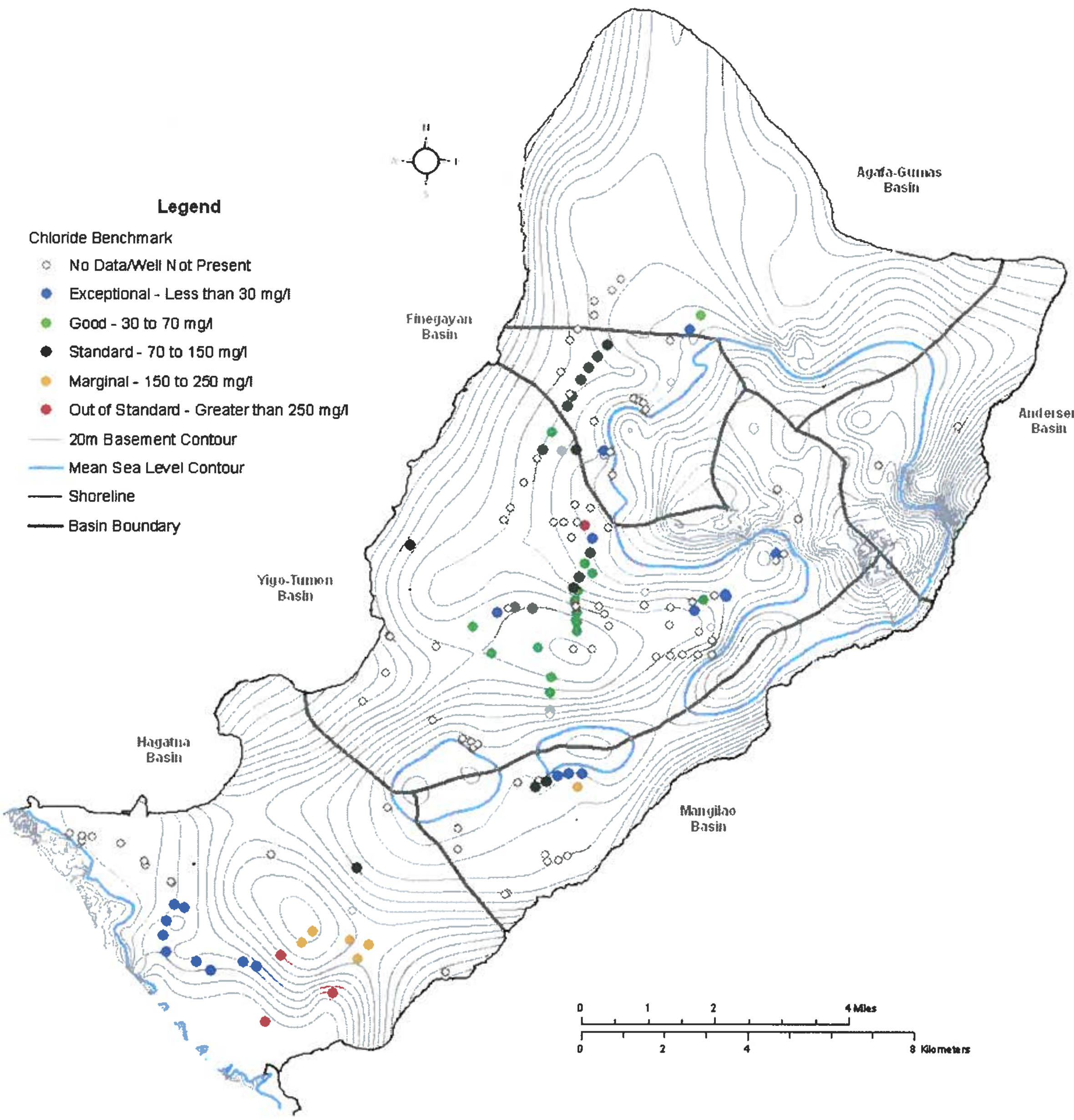


**Figure 6**: 1973 to 1979 mean decadal chloride concentrations in NGLA production wells.

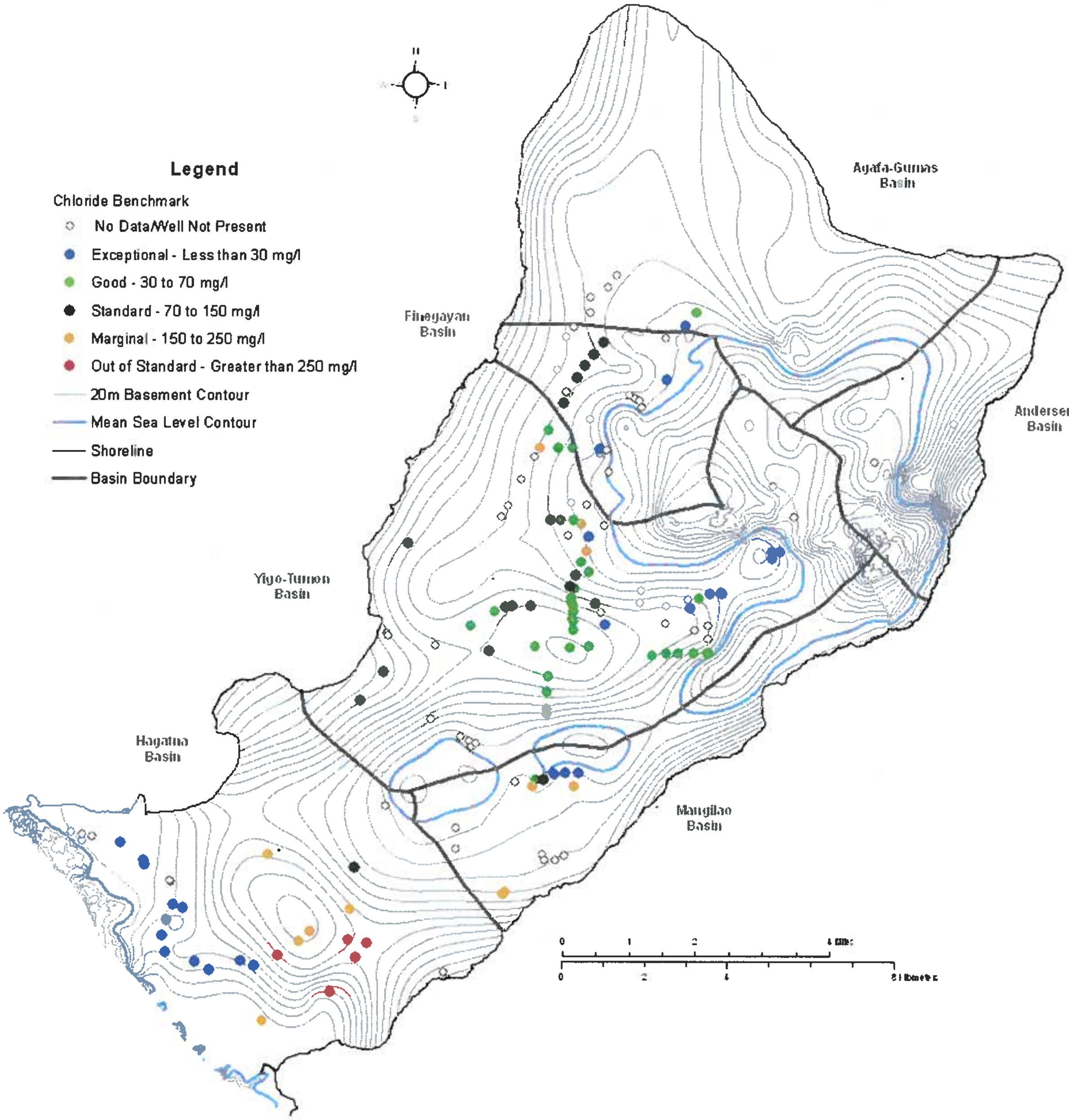


**Figure 7**: 1980 to 1989 mean decadal chloride concentrations in NGLA production wells.

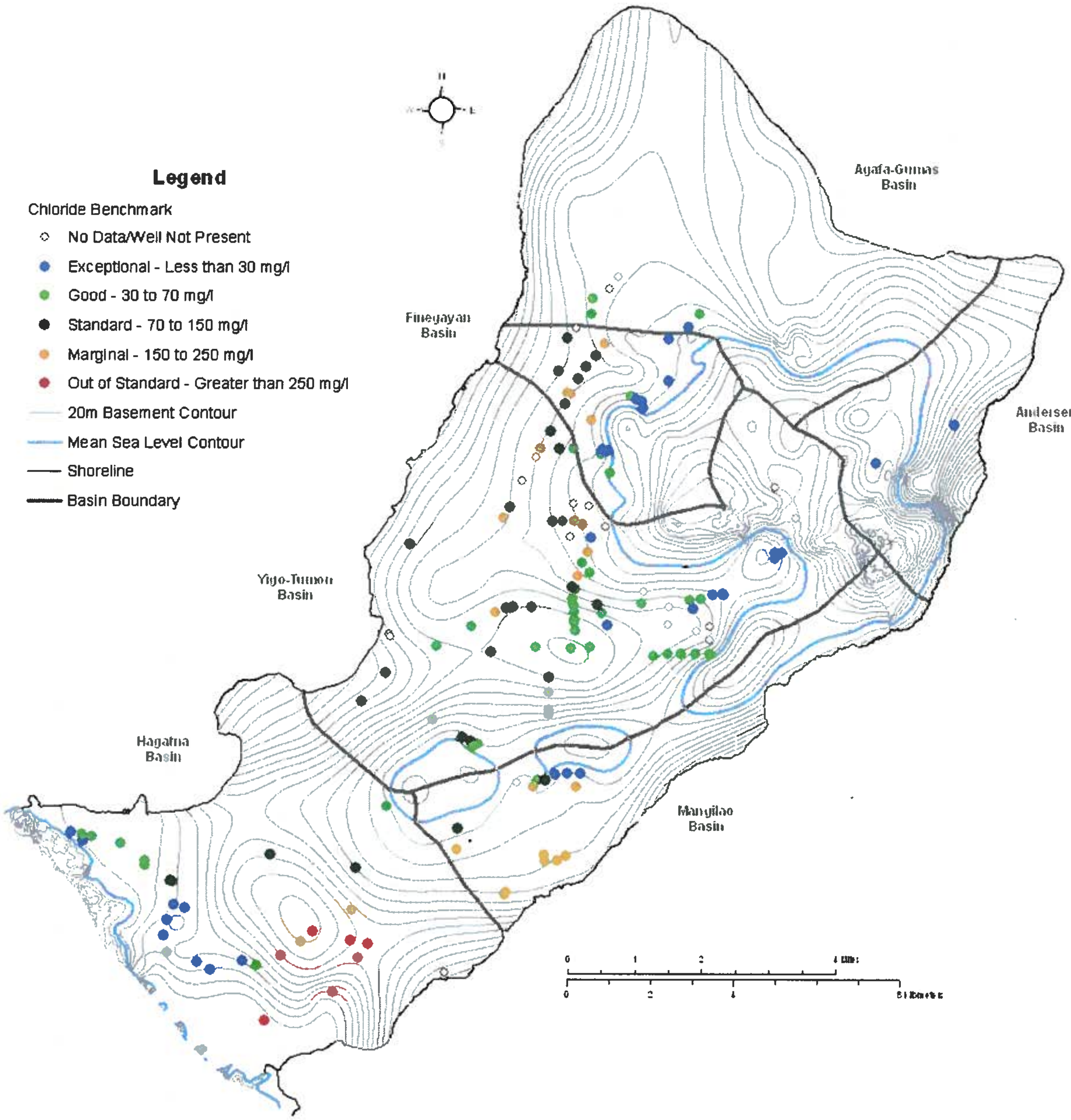


**Figure 8**: 1990 to 1999 mean decadal chloride concentrations in NGLA production wells.

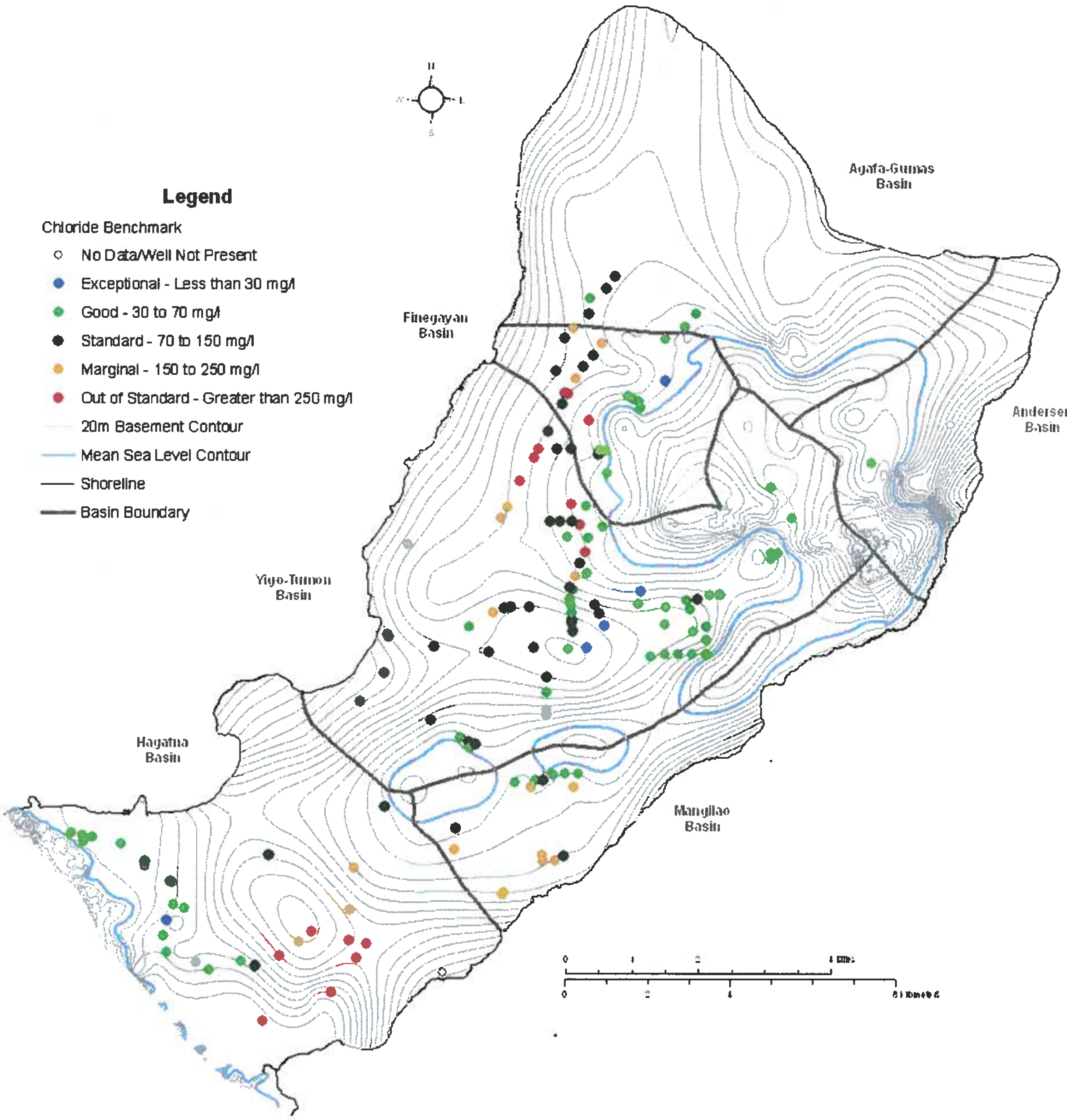


**Figure 9**: 2000 to 2010 mean decadal chloride concentrations in NGLA production wells.

## 5.2 Analysis of Chloride and Aquifer Management Data

Groundwater salinity is strongly influenced by well characteristics and management practices at each of the production wells, specifically location, construction, and groundwater extraction rate. This section evaluates basic management information, including chloride concentrations, for each production well across the NGLA within each of the six NGLA basins.

Of all freshwater production over the past few decades, GWA production has accounted for 78-93%, Air Force production has accounted for 4-12%, Navy production for 1-8%, and private production for 0.5-4%. As of December 2009, freshwater production was divided as follows: GWA at 90%, Air Force at 4%, Navy at 5%, and private at 1%.

Table 10 presents the mean decadal production from the private freshwater production wells and their permitted annual volumes set by Guam EPA. Private freshwater production is often greatly below the GEPA-permitted annual volumes. Freshwater production has also reduced between the 1990s and 2000s at 7 of 10 private wells.

**Table 10**: Summary of the permitted annual volume and mean decadal production for each private freshwater production well.

| Private Production Well | Permitted Annual Volume (Mgals/year) | Mean Decadal Production (Mgals/year) | |
|---|---|---|---|
| | | 1990-99 | 2000-10 |
| FM-1/1A | 65.7 | 32.4 | 23.5 |
| GPH-1 | 52.5 | 19.2 | 15.4 |
| GPH-2 | 52.5 | NA | 17.6 |
| HGC-3 | 315.3 | 54.7 | 58.1 |
| HRP-1 | 157.6 | 44.5 | 53.8 |
| HRP-2 | 157.6 | 16.7 | 48 |
| MGC-1 | 105.1 | 25.4 | 19 |
| MGC-2 | 105.1 | 24.5 | 16 |
| MGC-3 | 105.1 | 18.8 | 1.2 |
| MGC-4 | 105.1 | 25.4 | 22.6 |
| PBI-1 | 105.1 | 15 | 7.1 |

Note:
Mgals/year - million gallons per year

Table 11 summarizes whether reported well bottom depths and pump rates comply with those recommended by NGLS well-design guidelines for the groundwater zone in which the well resides. Each well was assigned to the basal or para-basal zone depending upon groundwater data collected from the monitoring well network and a saltwater toe location inferred from the volcanic basement map contour elevations (Vann et al. 2014).

The tabulated chloride and production statistics for each production well, according to basin, are provided in Tables 12 through 17. In each well summary table, the mean decadal chloride concentrations are color-coded to match their respective chloride benchmarks. Bolded values for well bottom depth and mean decadal production rate indicate an exceedance of the respective NGLS guidelines. Maps of each groundwater basin, including the production wells (showing the 2000-2010 mean decadal chloride concentration), monitoring wells, and volcanic basement contours (20 meter intervals), are included as Figures 10 through 15.

### Agafa Gumas Basin

The Agafa Gumas Basin (Figure 10; Table 12) is one of the largest basins in the NGLA, with a large northern coastline and basal groundwater zone. There are six productions wells, two monitoring wells, and three test borings in the Agafa Gumas Basin. The minus 40-meter volcanic basement contour is considered the boundary between the para-basal and basal groundwater zones. NAVFACMAR production wells NCS-6, NCS-7, NCS-11, and NCS-12 are situated in the basal groundwater zone, and GWA production wells AG-1 and AG-2A are situated in the para-basal groundwater zone.

In general, chloride concentrations in the Agafa Gumas Basin are considered "Good," being between 30 and 70 mg/l chloride. Chlorides at AG-2A were "Exceptional," being below 30 mg/l in the 1980s and 1990s, and NCS-11 and NCS-12 have been consistently below 100

## Table 11: Comparison of NGLA production wells to NGLS well design guidelines

| Production Well | Basin | Meets NGLS Well Design Guidelines | |
|---|---|---|---|
| | | Bottom Depth | Pump Rate |
| **Para-basal Groundwater** | | | |
| A-1 | Hagatña | NO | YES |
| A-3 | Hagatña | NO | YES |
| A-5 | Hagatña | NO | YES |
| A-6 | Hagatña | NO | YES |
| A-7 | Hagatña | NO | YES |
| A-8 | Hagatña | NO | YES |
| A-12 | Hagatña | NO | YES |
| A-17 | Hagatña | YES | YES |
| A-19 | Hagatña | YES | YES |
| A-23 | Hagatña | YES | YES |
| A-25 | Hagatña | NO | YES |
| A-29 | Hagatña | YES | YES |
| A-30 | Hagatña | YES | NO |
| A-31 | Hagatña | NO | YES |
| A-32 | Hagatña | NO | YES |
| AFMW-5/5A | Yigo-Tumon | NO (1965) / YES (2010) | UNKNOWN |
| AG-1 | Agafa Gumas | YES | YES |
| AG-2A | Agafa Gumas | NO | NO |
| D-12 | Yigo-Tumon | YES | YES |
| D-13 | Finegayan | NO | YES |
| D-19 | Yigo-Tumon | YES | YES |
| D-24 | Finegayan | NO | YES |
| D-25 | Yigo-Tumon | NO | YES |
| D-26 | Yigo-Tumon | YES | YES |
| D-27 | Yigo-Tumon | NO | YES |
| EX-11 | Mangilao | NO | YES |
| F-8 | Finegayan | YES | YES |
| F-12 | Finegayan | YES | YES |
| F-15 | Finegayan | NO | YES |
| F-16 | Finegayan | NO | YES |
| F-17 | Finegayan | NO | YES |
| F-18 | Finegayan | NO | YES |
| HGC-2 | Finegayan | NO | YES |
| HGC-3 | Finegayan | UNKNOWN | UNKNOWN |
| M-1 | Mangilao | YES | YES |
| M-2 | Mangilao | NO | YES |
| M-3 | Mangilao | NO | YES |
| M-4 | Mangilao | NO | YES |
| M-8 | Mangilao | YES | YES |
| M-17A | Yigo-Tumon | NO | YES |
| M-17B | Yigo-Tumon | YES | YES |
| M-20A | Yigo-Tumon | YES | YES |
| M-23 | Mangilao | NO | YES |
| NAS-1 | Hagatña | NO | YES |
| NCS-3/3A | Mangilao | YES | UNKNOWN |
| NCS-8 | Mangilao | UNKNOWN | UNKNOWN |
| NRMC-1 | Hagatña | NO | UNKNOWN |
| NRMC-2 | Hagatña | NO | UNKNOWN |
| NRMC-3 | Hagatña | YES | UNKNOWN |
| PBI-1 | Yigo-Tumon | NO | UNKNOWN |
| **Basal Groundwater** | | | |
| A-2 | Hagatña | YES | YES |
| A-4 | Hagatña | YES | YES |
| A-9 | Hagatña | NO | NO |
| A-10 | Hagatña | YES | NO |
| A-13 | Hagatña | NO | YES |
| A-14 | Hagatña | NO | NO |
| A-15 | Hagatña | NO | NO |
| A-18 | Hagatña | NO | NO |
| A-21 | Hagatña | NO | NO |
| A-26 | Hagatña | NO | YES |
| A-28 | Hagatña | YES | NO |
| AFMW-1 | Yigo-Tumon | NO | UNKNOWN |
| AFMW-2 | Yigo-Tumon | YES | UNKNOWN |
| AFMW-3 | Yigo-Tumon | YES | UNKNOWN |
| AFMW-6/6A | Yigo-Tumon | NO (1965) / YES (2010) | UNKNOWN |
| AFMW-7/7A | Yigo-Tumon | NO | UNKNOWN |
| AFMW-8/8A | Yigo-Tumon | YES | UNKNOWN |
| AFMW-9/9A | Yigo-Tumon | YES | UNKNOWN |
| BPM-1 | Andersen | NO (1955) / YES (2009) | UNKNOWN |
| D-1 | Yigo-Tumon | YES | NO |
| D-2 | Yigo-Tumon | YES | YES |
| D-3 | Yigo-Tumon | YES | YES |
| D-4 | Yigo-Tumon | YES | YES |
| D-5 | Yigo-Tumon | YES | YES |

| Production Well | Basin | Meets NGLS Well Design Guidelines | |
|---|---|---|---|
| | | Bottom Depth | Pump Rate |
| **Basal Groundwater** | | | |
| D-6 | Yigo-Tumon | YES | YES |
| D-7 | Yigo-Tumon | NO | NO |
| D-8 | Yigo-Tumon | YES | YES |
| D-9 | Yigo-Tumon | YES | YES |
| D-10 | Yigo-Tumon | YES | NO |
| D-11 | Yigo-Tumon | YES | NO |
| D-14 | Yigo-Tumon | NO | YES |
| D-15 | Yigo-Tumon | NO | NO |
| D-16 | Yigo-Tumon | NO | YES |
| D-17 | Yigo-Tumon | YES | YES |
| D-18 | Yigo-Tumon | NO | YES |
| D-20 | Yigo-Tumon | NO | NO |
| D-21 | Yigo-Tumon | NO | YES |
| D-28 | Yigo-Tumon | NO | YES |
| EX-5A | Yigo-Tumon | YES | NO |
| F-1 | Finegayan | YES | YES |
| F-2 | Finegayan | NO | YES |
| F-3 | Finegayan | NO | YES |
| F-4 | Finegayan | YES | YES |
| F-5 | Yigo-Tumon | YES | YES |
| F-6 | Yigo-Tumon | YES | NO |
| F-7 | Yigo-Tumon | YES | YES |
| F-9 | Yigo-Tumon | YES | YES |
| F-10 | Finegayan | YES | YES |
| F-11 | Finegayan | YES | YES |
| F-13 | Finegayan | YES | YES |
| F-19 | Finegayan | NO | YES |
| F-20 | Finegayan | NO | YES |
| FM-1/1A | Yigo-Tumon | YES | UNKNOWN |
| GH-501 | Yigo-Tumon | NO | YES |
| GPH-1 | Yigo-Tumon | UNKNOWN | UNKNOWN |
| GPH-2 | Yigo-Tumon | UNKNOWN | UNKNOWN |
| H-1 | Yigo-Tumon | NO | NO |
| HRP-1 | Mangilao | NO | UNKNOWN |
| HRP-2 | Mangilao | NO | UNKNOWN |
| M-5 | Yigo-Tumon | NO | YES |
| M-6 | Yigo-Tumon | NO | YES |
| M-7 | Yigo-Tumon | NO | YES |
| M-9 | Mangilao | NO | YES |
| M-12 | Yigo-Tumon | NO | YES |
| M-14 | Yigo-Tumon | NO | NO |
| M-15 | Yigo-Tumon | NO | YES |
| M-18 | Yigo-Tumon | NO | NO |
| M-21 | Yigo-Tumon | YES | YES |
| MGC-1 | Mangilao | UNKNOWN | UNKNOWN |
| MGC-2 | Mangilao | UNKNOWN | UNKNOWN |
| MGC-3 | Mangilao | UNKNOWN | UNKNOWN |
| MGC-4 | Mangilao | UNKNOWN | UNKNOWN |
| NCS-A | Finegayan | NO | UNKNOWN |
| NCS-B/B1 | Finegayan | UNKNOWN | UNKNOWN |
| NCS-2/2A | Yigo-Tumon | NO | UNKNOWN |
| NCS-5 | Yigo-Tumon | UNKNOWN | UNKNOWN |
| NCS-6 | Agafa Gumas | UNKNOWN | UNKNOWN |
| NCS-7 | Agafa Gumas | UNKNOWN | UNKNOWN |
| NCS-9/9A | Finegayan | UNKNOWN | UNKNOWN |
| NCS-10 | Finegayan | YES | UNKNOWN |
| NCS-11 | Agafa Gumas | YES | UNKNOWN |
| NCS-12 | Agafa Gumas | YES | UNKNOWN |
| TMT-1 | Yigo-Tumon | NOT APPLICABLE | NOT APPLICABLE |
| Y-2 | Yigo-Tumon | NO | YES |
| Y-3 | Yigo-Tumon | YES | YES |
| Y-4/4A | Yigo-Tumon | NO | YES |
| Y-5 | Yigo-Tumon | NO | YES |
| Y-6 | Yigo-Tumon | NO | YES |
| Y-7 | Yigo-Tumon | YES | NO |
| Y-9 | Yigo-Tumon | NO | NO |
| Y-10 | Yigo-Tumon | NO | NO |
| Y-12 | Yigo-Tumon | NO | NO |
| Y-14 | Yigo-Tumon | YES | NO |
| Y-16 | Yigo-Tumon | NO | YES |
| Y-18 | Yigo-Tumon | NO | NO |
| Y-19 | Yigo-Tumon | NO | NO |
| Y-20 | Yigo-Tumon | NO | NO |
| Y-21A | Yigo-Tumon | YES | NO |
| Y-22 | Yigo-Tumon | NO | YES |

Notes:
No NGLS guidelines were created for production wells in a supra-basal groundwater zone.
The NGLA supra-basal wells include: D-22A, Y-15, Y-17, and Y-23.

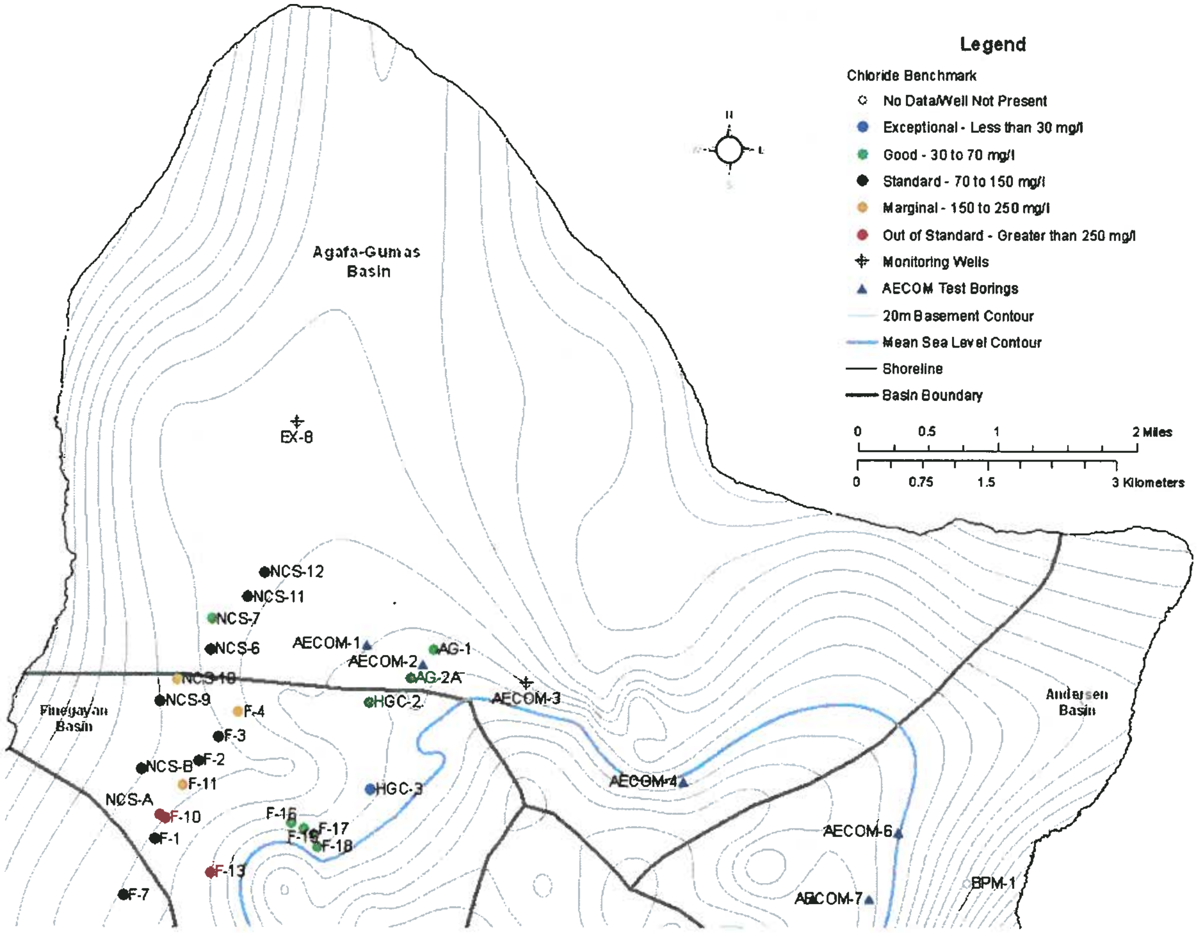


**Figure 10**: Agafa Gumas Basin map.

**Table 12**: Agafa Gumas Basin production well statistics.

| **Production Statistics** | | **AG-1** | **AG-2A** | **NCS-6** | **NCS-7** | **NCS-11** | **NCS-12** |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Para-basal | Para-basal | Basal | Basal | Basal | Basal |
| Well Bottom Elevation | feet | -27 | -81.2 | Unknown | Unknown | -35.75 | -36.5 |
| | meters | -8.23 | -24.75 | Unknown | Unknown | -10.90 | -11.13 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -50 | -50 | -40 | -40 | -40 | -40 |
| Well Screen Length (feet) | | Unknown | 60 | Unknown | Unknown | Unknown | Unknown |
| Well Construction Year | | 1967 | 1978 | Unknown | Unknown | 2006 | 2006 |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 500 | 500 | 200 | 200 | 200 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | 153.7 [1] | 146.4 [1] | NA | NA | NA | NA |
| | 1990 - 1999 | 141.3 [1] | 111.3 [1] | 7.81 [2] | 9.04 [2] | NA | NA |
| | 2000 - 2010 | 107.1 [1] | 521.1 [1] | 7.90 [2] | 8.44 [2] | 6.01 [2] | 6.54 [2] |
| **Chloride Statistics** | | **AG-1** | **AG-2A** | **NCS-6** | **NCS-7** | **NCS-11** | **NCS-12** |
| Total Number of Chloride Samples | | 171 | 153 | 335 | 321 | 29 | 32 |
| Minimum Concentration (mg/l) | | 13.6 | 10.0 | 20.0 | 16.5 | 66.3 | 52.0 |
| Maximum Concentration (mg/l) | | 71.5 | 60.5 | 190.0 | 95.9 | 99.9 | 115.0 |
| Standard Deviation | | 11.9 | 10.5 | 21.5 | 13.9 | 8.0 | 15.6 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | 35.2 | 17.9 | NA | NA | NA | NA |
| | 1980 - 1989 | 40.7 | 18 | NA | NA | NA | NA |
| | 1990 - 1999 | 44.4 | 22.4 | 55.5 | 36.6 | NA | NA |
| | 2000 - 2010 | 58.2 | 36.9 | 70.5 | 46.7 | 86 | 89.1 |

mg/l since their construction in 2006. Linear regression of chloride concentrations indicates a significant increasing trend at AG-1, AG-2A and NCS-12, no significant increasing trend at NCS-6, and no significant decreasing trend at NCS-7 and NCS-11 (Appendix C).

As shown in Table 12, NGLS guidelines are only exceeded at para-basal production well AG-2A. The well bottom depth (-81.2 feet) and average decadal pump rate from 2000-2010 (521.1 gpm) exceed the NGLS guidelines for the para-basal zone, and yet AG-2A still yields low salinity groundwater. Pump rates at the Navy-owned production wells are reported in millions of gallons per month (Mgal/month), rather than gpm, and could not be compared to NGLS guidelines.

Hydraulic head measurements are highly variable throughout the Agafa Gumas Basin. During 2010 AECOM drilling activities, hydraulic head measurements ranged from roughly 4 feet at test borings AECOM-1 and AECOM-2, to 31 feet at monitoring well AECOM-3, to 121 feet at test boring AECOM-4 (AECOM 2011). Hydraulic head measurements at monitoring well EX-8, recorded sporadically in the 1980s and 2000s, ranged from 1.9 to 4.5 feet.

**Andersen Basin**

The Andersen Basin (Figure 11; Table 13), located in the northwest region of Guam, contains two production wells and three AECOM test borings evaluated for this study. Production wells Y-15 and BPM-1 are constructed and operated very differently, and they both exhibit relatively low chloride concentrations for different reasons. Remarkably, production well Y-15 is situated in a supra-basal groundwater zone at approximately +77 feet elevation and sustains a relatively high production rate of 550 to 600 gpm. Low chlorides at Y-15 are attributed to its location in the supra-basal groundwater zone, which is not hydraulically connected to seawater. Production well BPM-1 is located in a basal groundwater zone and operates as needed for irrigation purposes producing less than 150,000 gallons per year. Low chlorides at BPM-1 are attributed to low pump rates and modest well depth.

Hydraulic head measurements obtained during 2010 AECOM drilling activities ranged from 208 feet at test boring AECOM-5, which encountered volcanic bedrock at +175 feet, to 2.4 to 3.2 feet at test borings AECOM-6 and AECOM-7, which did not encounter volcanic bedrock at their terminal depths of -60 feet (AECOM 2011).

Linear regression analysis indicates that Y-15 shows a significant increasing trend and BPM-1 shows no significant decreasing trend (Appendix C). Mean decadal production increased at Y-15 by 6% between the 1990s and 2000s, which corresponded to a 55% increase in mean decadal chloride concentration; however, groundwater quality is still considered "Good," being between 30 and 70 mg/l chloride. There are no well design guidelines for supra-basal production wells, such as Y-15. Groundwater elevations at nearby test boring AECOM-7 were less than 4 feet during 2010; therefore, production well BPM-1 was compared to the NGLS guideline for basal groundwater zones. The mean decadal pump rate at BPM-1 meets NGLS guidelines, but only the 2009 well depth meets the NGLS termination depth guideline, not the original 1955 depth.

**Finegayan Basin**

The Finegayan Basin (Figure 12; Table 14) is the smallest NGLA basin in terms of surface area and coastline, and contains 21 production wells. Although NCS-A was recently converted to a monitoring well (2010), it was evaluated as a production well for this study. The minus 40-meter volcanic basement contour is considered the boundary between the para-basal and basal groundwater zones. Eleven (11) of the 21 production wells are situated in the basal groundwater zone, and all exhibit "Standard" to "Out of Standard" chloride concentrations. Nine production wells are situated in the para-basal groundwater zone and exhibit "Exceptional" to "Standard" chloride concentrations. One production well (D-22A) is situated in the supra-basal groundwater zone and exhibits "Good" chloride concentrations.

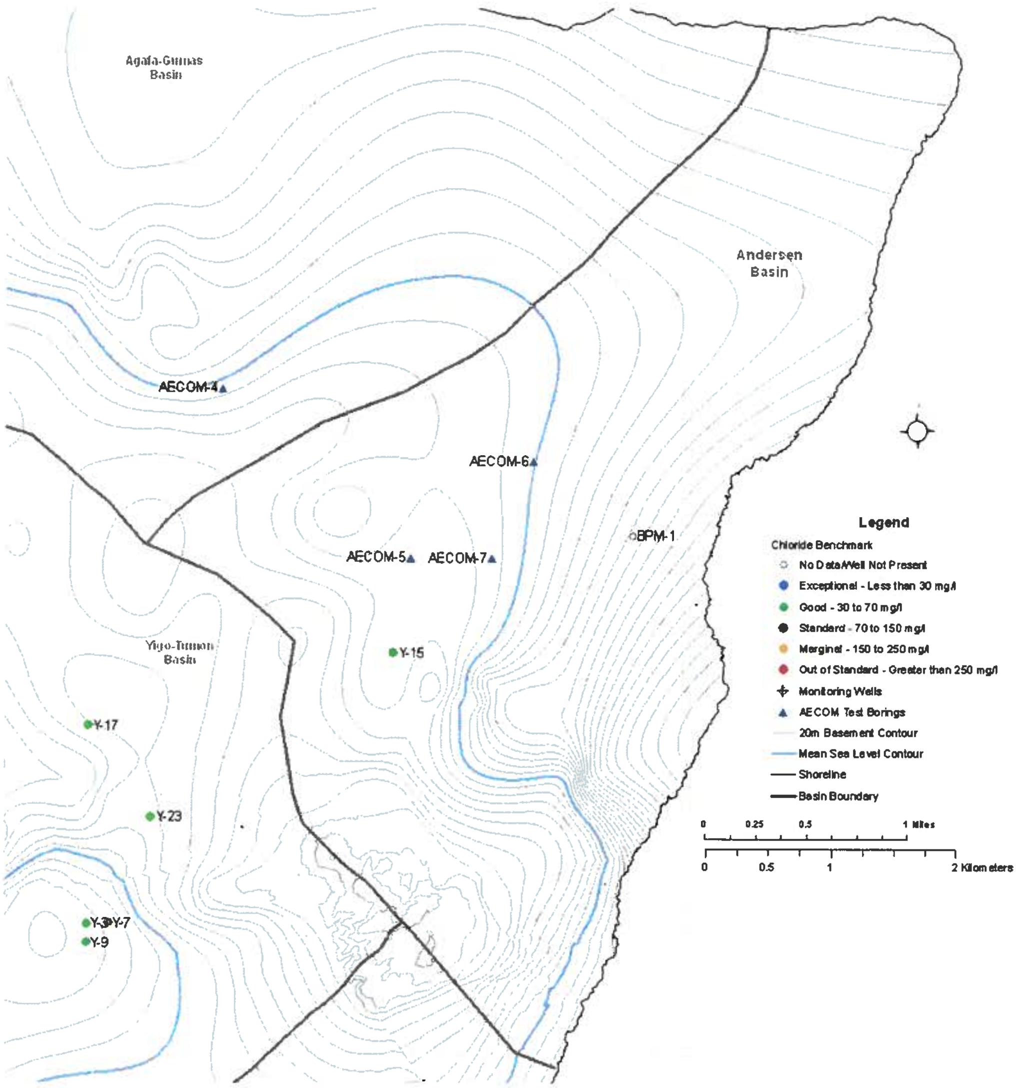


**Figure 11**: Andersen Basin map.

**Table 13**: Andersen Basin production well statistics.

| Production Statistics | | Y-15 | BPM-1 |
|---|---|---|---|
| Groundwater Zone | | Supra-basal | Basal |
| Well Depth Elevation | feet | 77.76 | **-43.78 / -32.53** |
| | meters | 23.70 | -13.34 / -9.92 |
| NGLS Max. Recommended Bottom Elevation (feet) | | NA | -40 |
| Screen Length (feet) | | Unknown | Unknown / 30 |
| Initial Year of Production | | 1995 | 1955 / 2009 |
| Status or Final Year of Production | | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | NA | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | NA | NA |
| | 1990 - 1999 | 560.2 [1] | 0.148 [2] |
| | 2000 - 2010 | 592.8 [1] | 0.146 [2] |
| **Chloride Statistics** | | **Y-15** | **BPM-1** |
| Total Number of Chloride Samples | | 59 | 6 |
| Minimum Concentration (mg/l) | | 6.0 | 21.8 |
| Maximum Concentration (mg/l) | | 59.8 | 33.0 |
| Standard Deviation | | 10.2 | 4.5 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA |
| | 1980 - 1989 | NA | NA |
| | 1990 - 1999 | 22.9 | 26.5 |
| | 2000 - 2010 | 35.6 | NA |

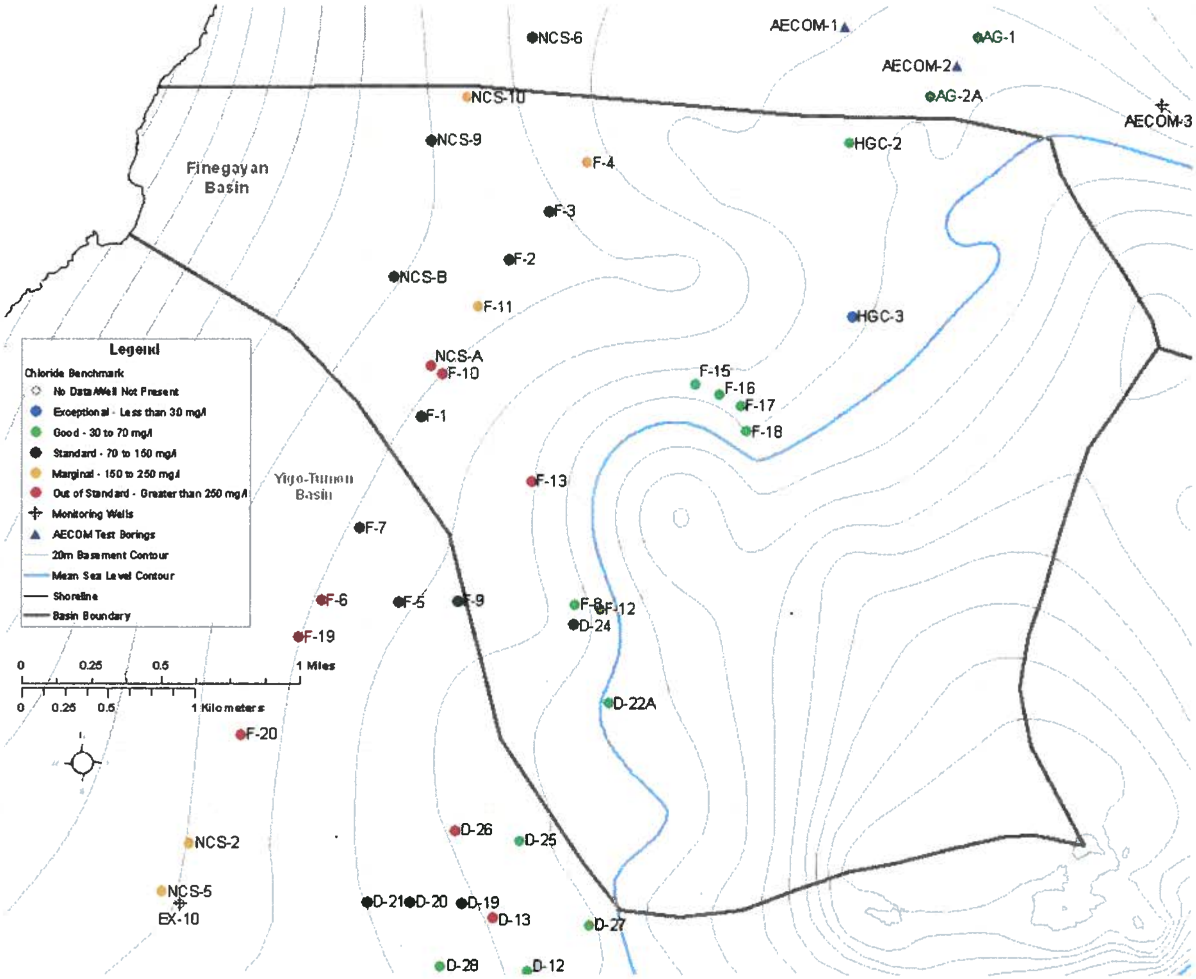


**Figure 12**: Finegayan Basin map.

**Table 14**: Finegayan Basin production well statistics.

| Production Statistics | | D-22A | D-24 | F-1 | F-2 | F-3 | F-4 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Supra-basal | Para-basal | Basal | Basal | Basal | Basal |
| Well Depth Elevation | feet | 5.91 | **-63.02** | -35.74 | **-40.76** | **-55.77** | -37.74 |
| | meters | 1.80 | -19.21 | -10.89 | -12.42 | -17.00 | -11.50 |
| NGLS Max. Recommended Bottom Elevation (feet) | | NA | -50 | -40 | -40 | -40 | -40 |
| Well Screen Length (feet) | | Unknown | Unknown | 45 | Unknown | 40 | 40 |
| Well Construction Year | | 1996 | 1995 | 1969 | 1971 | 1975 | 1975 |
| Status / Final Year of Production | | 2009 | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | NA | 500 | 200 | 200 | 200 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | NA | NA | 159 [1] | 167.4 [1] | 117 [1] | 137.5 [1] |
| | 1990 - 1999 | 111.8 [1] | 116.5 [1] | 141.3 [1] | 119.5 [1] | 146.6 [1] | 132.1 [1] |
| | 2000 - 2010 | 152.1 [1] | 184.8 [1] | 148.2 [1] | 137.9 [1] | 150.7 [1] | 151 [1] |
| **Chloride Statistics** | | **D-22A** | **D-24** | **F-1** | **F-2** | **F-3** | **F-4** |
| Total Number of Chloride Samples | | 34 | 37 | 214 | 202 | 199 | 191 |
| Minimum Concentration (mg/l) | | 14.0 | 28.0 | 54.0 | 11.2 | 16.1 | 15.5 |
| Maximum Concentration (mg/l) | | 218.9 | 205.9 | 233.9 | 237.5 | 184.2 | 336.9 |
| Standard Deviation | | 36.8 | 35.0 | 37.8 | 25.5 | 24.1 | 68.3 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | **72.6** | **102.9** | **92.2** | **82.5** |
| | 1980 - 1989 | NA | NA | **86.6** | **112.9** | **106.3** | **139.1** |
| | 1990 - 1999 | 30.7 | 42.5 | **99.3** | **117.5** | **107.3** | 167.3 |
| | 2000 - 2010 | 47.7 | **90.2** | **148.6** | **145.8** | **126.4** | 192.7 |

**Table 14:** Continued.

| Production Statistics | | F-8 | F-10 | F-11 | F-12 | F-13 | F-15 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Para-basal | Basal | Basal | Para-basal | Basal | Para-basal |
| Well Depth Elevation | feet | -18.34 | **-47.29** | **-47.06** | -41.33 | **-53.78** | **-51.47** |
| | meters | -5.59 | -14.41 | -14.34 | -12.60 | -16.39 | -15.69 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -50 | -40 | -40 | -50 | -40 | -50 |
| Well Screen Length (feet) | | 30 | 40 | 40 | 40 | Unknown | Unknown |
| Well Construction Year | | 1975 | 1978 | 1978 | 1990 | 1992 | 1995 |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 500 | 200 | 200 | 500 | 200 | 500 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | 134.7 [1] | 165.4 [1] | 154.9 [1] | NA | NA | NA |
| | 1990 - 1999 | 146.9 [1] | 146.9 [1] | 146.9 [1] | 142.2 [1] | **222.6** [1] | 357 [1] |
| | 2000 - 2010 | 157.6 [1] | **202.1** [1] | 168.3 [1] | 191.6 [1] | **237.4** [1] | 234.2 [1] |
| **Chloride Statistics** | | **F-8** | **F-10** | **F-11** | **F-12** | **F-13** | **F-15** |
| Total Number of Chloride Samples | | 182 | 150 | 155 | 78 | 57 | 61 |
| Minimum Concentration (mg/l) | | 12.1 | 24.0 | 71.8 | 12.0 | 22.0 | 22.0 |
| Maximum Concentration (mg/l) | | 142.9 | 468.0 | 243.5 | 272.9 | 381.0 | 156.0 |
| Standard Deviation | | 18.2 | 86.5 | 43.1 | 32.8 | 76.6 | 21.7 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | 17 | **145.7** | **110.4** | NA | NA | NA |
| | 1980 - 1989 | 24.1 | 163 | **109.9** | NA | NA | NA |
| | 1990 - 1999 | 24.9 | 190.5 | **126.7** | 25 | 200.8 | 58.1 |
| | 2000 - 2010 | 54.9 | 291.9 | 174.4 | 48.9 | 260.6 | 61.6 |

| Production Statistics | | F-16 | F-17 | F-18 | HGC-2 | HGC-3 | NCS-A |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Para-basal | Para-basal | Para-basal | Para-basal | Para-basal | Basal |
| Well Depth Elevation | feet | **-50.14** | **-62.8** | **-62.93** | **-81.95** | Unknown | **-50.32** |
| | meters | -15.28 | -19.14 | -19.18 | -24.98 | Unknown | -15.34 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -50 | -50 | -50 | -50 | -50 | -40 |
| Well Screen Length (feet) | | Unknown | Unknown | Unknown | 60 | Unknown | 35 |
| Well Construction Year | | 1995 | 1995 | 1995 | 1987 | Unknown | 1954 |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | Operational | 2010 |
| NGLS Max. Recommended Pump Rate (gpm) | | 500 | 500 | 500 | 500 | 500 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | NA | NA | NA | NA | NA | NA |
| | 1990 - 1999 | 159.6 [1] | 273 [1] | 192.4 [1] | 394.4 [1] | 4.6 [2] * | 6.58 [2] |
| | 2000 - 2010 | 319.2 [1] | 211.2 [1] | 319 [1] | **516.6** [1] | 4.8 [2] * | 4.1 [2] |
| **Chloride Statistics** | | **F-16** | **F-17** | **F-18** | **HGC-2** | **HGC-3** | **NCS-A** |
| Total Number of Chloride Samples | | 59 | 53 | 53 | 70 | 9 | 323 |
| Minimum Concentration (mg/l) | | 6.0 | 12.5 | 10.0 | 11.0 | 8.8 | 23.7 |
| Maximum Concentration (mg/l) | | 77.0 | 80.0 | 109.6 | 75.2 | 21.3 | 578.0 |
| Standard Deviation | | 33.3 | 12.2 | 14.7 | 11.9 | 3.5 | 78.3 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | NA | NA | NA | NA |
| | 1980 - 1989 | NA | NA | NA | NA | 13 | NA |
| | 1990 - 1999 | 20.9 | 18.7 | 18 | 22.4 | 13.6 | 228.8 |
| | 2000 - 2010 | 39.2 | 32.9 | 33.7 | 36.6 | 15.3 | 285.4 |

Note: * - Mgal/mo value obtained from annual production volume averaged over 12 months

| Production Statistics | | NCS-B/B1 | NCS-9/9A | NCS-10 |
|---|---|---|---|---|
| Groundwater Zone | | Basal | Basal | Basal |
| Well Depth Elevation | feet | Unknown | Unknown | -35.3 |
| | meters | Unknown | Unknown | -10.76 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -40 | -40 | -40 |
| Well Screen Length (feet) | | Unknown | Unknown | Unknown |
| Well Construction Year | | Unknown | Unknown | 2003 |
| Status / Final Year of Production | | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 | 200 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | NA | NA | NA |
| | 1990 - 1999 | 7.19 [2] | 9.03 [2] | NA |
| | 2000 - 2010 | 9.39 [2] | 7.95 [2] | 5.16 [2] |
| **Chloride Statistics** | | **NCS-B/B1** | **NCS-9/9A** | **NCS-10** |
| Total Number of Chloride Samples | | 186 | 275 | 33 |
| Minimum Concentration (mg/l) | | 38.0 | 11.5 | 130.0 |
| Maximum Concentration (mg/l) | | 206.0 | 184.0 | 229.0 |
| Standard Deviation | | 24.3 | 30.8 | 26.8 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | NA |
| | 1980 - 1989 | NA | NA | NA |
| | 1990 - 1999 | **109.4** | **86.2** | NA |
| | 2000 - 2010 | **115.8** | **100** | 181.8 |

Linear regression analysis indicates that 14 production wells show significant increasing trends, NCS-A and NCS-B show a significant decreasing trend, and four production wells (D-22A, F-13, F-15 and HGC-3) show no significant increasing trend (Appendix C). Chloride concentrations were higher during the 2000-10 decade than any of the previous decades in all 19 of the production wells with more than one decade of chloride data.

Hydraulic head is inferred to be less than 4 feet in the basal groundwater zone of the Finegayan Basin based on historical groundwater levels at monitoring well EX-10 in the southern Yigo-Tumon Basin and monitoring well EX-8 in the northern Agafa Gumas Basin.

Of the 11 basal production wells, two mean decadal pump rates (F-10 and F-13) exceed the NGLS guideline of 200 gpm, and seven well bottom depths (D-24, F-2, F-3, F-10, F-11, F-13 and NCS-A) exceed the NGLS guideline of -40 feet. Of the nine para-basal production wells, the mean decadal pump rate at HGC-2 exceeds the NGLS guideline of 500 gpm, and five bottom depths (F-15, F-16, F-17, F-18 and HGC-2) exceed the NGLS guideline of -50 feet. There are no well design guidelines for supra-basal production well D-22A. Well bottom depths are unknown at NCS-B, NCS-9A and HGC-3.

**Hagåtña Basin**

The Hagåtña Basin (Figure 13; Table 15) is the southernmost and second largest NGLA basin after the Yigo-Tumon Basin. The boundary between the para-basal and basal groundwater zones is considered the minus 80-meter volcanic basement contour in the southern region and the minus 40-meter volcanic basement contour in the northern region. There are 30 total production wells in the Hagåtña Basin, with 19 situated in a para-basal groundwater zone and 11 situated in a basal groundwater zone.

Chloride concentrations range from "Exceptional" for those in the para-basal groundwater zones in the southern region to "Out of Standard" for those in the southeast basal groundwater zone. The southeast Hagåtña Basin contains seven of the 16 NGLA production wells with "Out of Standard" chloride concentrations. Among those wells, production well A-19 exhibits anomalously high chloride concentrations despite its location in a para-basal groundwater zone between the MSL and minus 20-meter volcanic basement contour.

Linear regression analysis indicates that 23 production wells show significant increasing trends, A-29 shows no significant increasing trend, NRMC-2 shows a significant decreasing trend, and five production wells (A-26, A-28, A-30, NRMC-1, and NRMC-3) show no significant decreasing trends (Appendix C). Chloride concentrations were higher during the 2000-10 decade than any of the previous decades in 27 of the 30 production wells. Also during 2000-10, mean decadal production rates were highest at 19 of those 27 production wells.

Based on historical groundwater levels at monitoring wells BPM-1, EX-1, EX-4, and EX-9, all situated in basal groundwater zones, hydraulic heads are generally greater than 4 feet in the southern region and less than 4 feet in the northern region near Barrigada Hill. Basal production wells in the southern region should be installed no deeper than -50 feet and pumped less than 350 gpm. Basal production wells in the northern region should be installed no deeper than -40 feet and pumped less than 200 gpm.

Production wells A-2, A-4 and A-13, which are situated between monitoring wells EX-1 and EX-4, are the only basal production wells in the NGLA compared to the NGLS guidelines where hydraulic head is consistently greater than 4 feet. Production wells A-2, A-4, and A-13 exceed the NGLS -50-foot bottom depth guideline, but all have mean decadal pump rates below the 350 gpm NGLS guideline. Of the eight remaining basal production wells, seven mean decadal pump rates exceed the NGLS guideline of 200 gpm (all except A-26), and six well bottom depths exceed the NGLS guideline of -40 feet (all except A-10 and A-28).

NGLS guidelines for para-basal groundwater zones in southern Hagåtña Basin specify that wells should be no deeper than -50 feet and pumped less than 200 gpm, allowing for 350 gpm under "special considerations". The NGLS, however, does not clearly define what

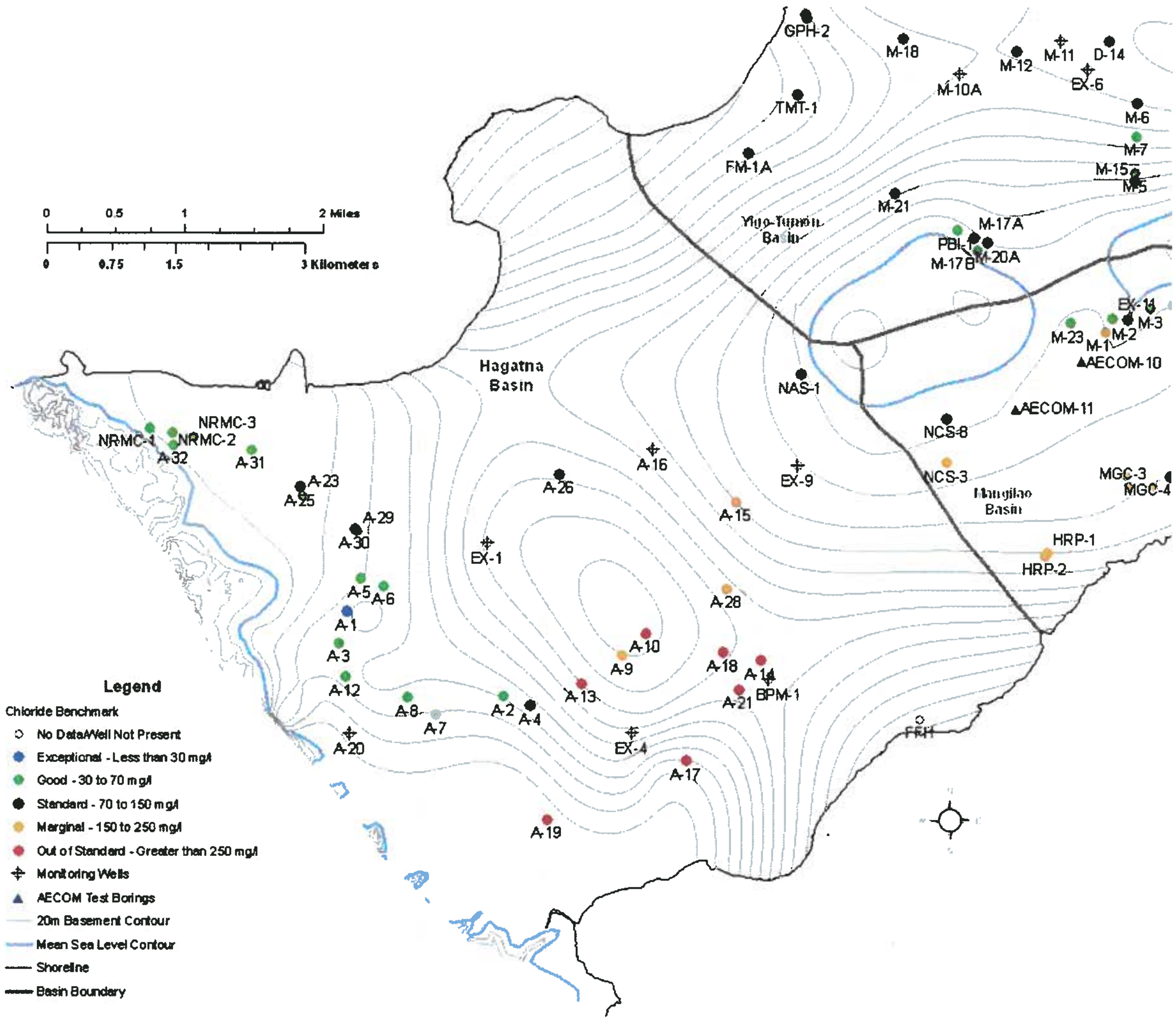


**Figure 13**: Hagåtña Basin map

**Table 15**: Hagåtña Basin production well statistics.

| Production Statistics | | A-1 | A-2 | A-3 | A-4 | A-5 | A-6 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Para-basal | Basal | Para-basal | Basal | Para-basal | Para-basal |
| Well Depth Elevation | feet | -153.3 | -54.04 | -262.52 | -159.75 | -186.04 | -152.86 |
| | meters | -46.73 | -16.47 | -80.02 | -48.69 | -56.70 | -46.59 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -50 | -50 | -50 | -50 | -50 | -50 |
| Well Screen Length (feet) | | 50 | 60 | Unknown | 160 | Unknown | 170 |
| Well Construction Year | | 1965 | 1965 | 1967 | 1967 | 1969 | 1967 |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 (350**) | 350 | 200 (350**) | 350 | 200 (350**) | 200 (350**) |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | 206.3 [1] | 198.2 [1] | 208.5 [1] | 185.2 [1] | 194.8 [1] | 211.4 [1] |
| | 1990 - 1999 | 250.3 [1] | 235.8 [1] | 217 [1] | 231.8 [1] | 234.9 [1] | 272.1 [1] |
| | 2000 - 2010 | 267.9 [1] | 231.1 [1] | 279.9 [1] | 317.3 [1] | 260.6 [1] | 308.2 [1] |
| **Chloride Statistics** | | **A-1** | **A-2** | **A-3** | **A-4** | **A-5** | **A-6** |
| Total Number of Chloride Samples | | 198 | 217 | 210 | 218 | 215 | 221 |
| Minimum Concentration (mg/l) | | 3.9 | 6.0 | 2.7 | 15.4 | 4.0 | 10.9 |
| Maximum Concentration (mg/l) | | 67.5 | 84.2 | 61.8 | 130.9 | 66.0 | 70.7 |
| Standard Deviation | | 7.5 | 9.1 | 7.1 | 26.2 | 9.0 | 11.7 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | 17.8 | 17.6 | 17.2 | 19.2 | 17.5 | 17.5 |
| | 1980 - 1989 | 18.6 | 20.9 | 18.3 | 23.4 | 18 | 20.3 |
| | 1990 - 1999 | 20.5 | 23.2 | 18.7 | 41.9 | 21.1 | 26.5 |
| | 2000 - 2010 | 29.2 | 37.3 | 30.1 | 82.1 | 35.9 | 44 |

Note: ** - NGLS allows para-basal wells 350 gpm under special considerations.

**Table 15**: Continued.

| Production Statistics | | A-7 | A-8 | A-9 | A-10 | A-12 | A-13 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Para-basal | Para-basal | Basal | Basal | Para-basal | Basal |
| Well Depth Elevation | feet | **-52.74** | **-175.09** | **-52.85** | -23.99 | **-190** | **-287.2** |
| | meters | -16.08 | -53.37 | -16.11 | -7.31 | -57.91 | -87.54 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -50 | -50 | -40 | -40 | -50 | -50 |
| Well Screen Length (feet) | | 70 | 205 | 73 | 44 | 225 | 213 |
| Well Construction Year | | 1967 | 1968 | 1967 | 1967 | 1968 | 1968 |
| Status / Final Year of Production | | 2002 | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 (350**) | 200 (350**) | 200 | 200 | 200 (350**) | 350 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | 194.7 [1] | 199.8 [1] | 174.8 [1] | 184.4 [1] | **215.3** [1] | 173.4 [1] |
| | 1990 - 1999 | 146.5 [1] | **230.6** [1] | **214.2** [1] | **210.9** [1] | 188.1 [1] | 230.1 [1] |
| | 2000 - 2010 | NA | **243.6** [1] | **289.3** [1] | **281.4** [1] | 189.1 [1] | 303.6 [1] |
| **Chloride Statistics** | | **A-7** | **A-8** | **A-9** | **A-10** | **A-12** | **A-13** |
| Total Number of Chloride Samples | | 186 | 209 | 213 | 216 | 221 | 217 |
| Minimum Concentration (mg/l) | | 11.0 | 7.9 | 36.3 | 28.2 | 11.9 | 46.0 |
| Maximum Concentration (mg/l) | | 60.0 | 235.1 | 420.0 | 480.8 | 422.0 | 670.2 |
| Standard Deviation | | 6.3 | 19.0 | 37.0 | 79.3 | 29.5 | 99.6 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | 19.7 | 17.2 | 154.6 | 188.3 | 16.9 | 270.4 |
| | 1980 - 1989 | 23.2 | 23.7 | 164.9 | 205.7 | 18.6 | 319.5 |
| | 1990 - 1999 | 26.3 | 20.6 | 187.4 | 287.1 | 30.1 | 371.3 |
| | 2000 - 2010 | 33.4 | 40.9 | 214.7 | 341.7 | 38.4 | 424.5 |
| **Production Statistics** | | **A-14** | **A-15** | **A-17** | **A-18** | **A-19** | **A-21** |
| Groundwater Zone | | Basal | Basal | Para-basal | Basal | Para-basal | Basal |
| Well Depth Elevation | feet | **-64.16** | **-52.24** | -47.7 | **-52.06** | -37.72 | **-66.25** |
| | meters | -19.56 | -15.92 | -14.54 | -15.87 | -11.50 | -20.19 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -40 | -40 | -50 | -40 | -50 | -40 |
| Well Screen Length (feet) | | 40 | 40 | 40 | 40 | 20 | 36 |
| Well Construction Year | | 1973 | 1973 | 1973 | 1973 | 1973 | 1973 |
| Status / Final Year of Production | | Operational | 2002 | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 | 200 | 200 (350**) | 200 | 200 (350**) | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | 179.3 [1] | 170.7 [1] | 168.4 [1] | 162.3 [1] | 119.2 [1] | 170 [1] |
| | 1990 - 1999 | **208.5** [1] | **239.7** [1] | **215.9** [1] | **207.3** [1] | 175.3 [1] | 199.4 [1] |
| | 2000 - 2010 | **250.4** [1] | **293.6** [1] | **244.5** [1] | **276.2** [1] | 193.6 [1] | **272.4** [1] |
| **Chloride Statistics** | | **A-14** | **A-15** | **A-17** | **A-18** | **A-19** | **A-21** |
| Total Number of Chloride Samples | | 210 | 211 | 205 | 192 | 197 | 206 |
| Minimum Concentration (mg/l) | | 100.0 | 22.0 | 88.4 | 94.0 | 32.0 | 41.0 |
| Maximum Concentration (mg/l) | | 393.7 | 274.4 | 714.2 | 520.3 | 493.0 | 514.3 |
| Standard Deviation | | 50.8 | 28.4 | 100.2 | 83.9 | 107.0 | 95.2 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | 236.4 | 135.1 | 280.7 | 230.3 | 282.5 | 204.3 |
| | 1980 - 1989 | 280.8 | 145.7 | 313.9 | 271.4 | 241.4 | 271.5 |
| | 1990 - 1999 | 295.2 | 145 | 349.6 | 391.8 | 355 | 353.2 |
| | 2000 - 2010 | 309.6 | 162.6 | 437 | 362 | 400.9 | 400.4 |
| **Production Statistics** | | **A-23** | **A-25** | **A-26** | **A-28** | **A-29** | **A-30** |
| Groundwater Zone | | Para-basal | Para-basal | Basal | Basal | Para-basal | Para-basal |
| Well Depth Elevation | feet | -42.6 | **-52.26** | **-49.29** | -40 | -45.36 | -23.44 |
| | meters | -12.98 | -15.93 | -15.02 | -12.19 | -13.83 | -7.14 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -50 | -50 | -40 | -40 | -50 | -50 |
| Well Screen Length (feet) | | Unknown | 40 | Unknown | Unknown | 40 | 40 |
| Well Construction Year | | 1983 | 1984 | 1983 | 1983 | 1988 | 1988 |
| Status / Final Year of Production | | Operational | Operational | Operational | 2006 | 2005 | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 (350**) | 200 (350**) | 200 | 200 | 200 (350**) | 200 (350**) |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | **235.4** [1] | **215.9** [1] | 108.8 [1] | 189.3 [1] | NA | NA |
| | 1990 - 1999 | **295.6** [1] | **260.5** [1] | 57.6 [1] | **227.4** [1] | **339.6** [1] | **680.4** [1] |
| | 2000 - 2010 | **334.6** [1] | **325.5** [1] | 52.5 [1] | **410.2** [1] | **289.5** [1] | **710** [1] |
| **Chloride Statistics** | | **A-23** | **A-25** | **A-26** | **A-28** | **A-29** | **A-30** |
| Total Number of Chloride Samples | | 109 | 104 | 87 | 87 | 47 | 81 |
| Minimum Concentration (mg/l) | | 16.0 | 17.0 | 38.0 | 22.0 | 12.0 | 17.0 |
| Maximum Concentration (mg/l) | | 103.0 | 128.9 | 555.9 | 349.0 | 162.0 | 300.0 |
| Standard Deviation | | 22.7 | 30.1 | 61.7 | 42.1 | 35.0 | 57.2 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | NA | NA | NA | NA |
| | 1980 - 1989 | 21.9 | 24.5 | 156.6 | 187.5 | NA | NA |
| | 1990 - 1999 | 37.8 | 50.8 | 82 | 171.9 | 65.3 | 103.2 |
| | 2000 - 2010 | 61 | 76.1 | 103.1 | 175 | 69 | 84.8 |

Note: ** - NGLS allows para-basal wells 350 gpm under special considerations.

**Table 15**: Continued.

| Production Statistics | | A-31 | A-32 | NAS-1 | NRMC-1 | NRMC-2 | NRMC-3 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Para-basal | Para-basal | Para-basal | Para-basal | Para-basal | Para-basal |
| Well Depth Elevation | feet | **-55.2** | **-56.15** | **-67.67** | -39.77 | **-55.3** | -40.9 |
| | meters | -16.82 | -17.11 | -20.63 | -12.12 | -16.86 | -12.47 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -50 | -50 | -50 | -50 | -50 | -50 |
| Well Screen Length (feet) | | Unknown | 40 | Unknown | Unknown | Unknown | Unknown |
| Well Construction Year | | 1989 | 1989 | 1973 | 1988 | 1989 | 1991 |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 (350**) | 200 (350**) | 500 | 200 (350**) | 200 (350**) | 200 (350**) |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | NA | NA | NA | NA | NA | NA |
| | 1990 - 1999 | **256.7** [1] | 134.2 [1] | NA | 7.88 [2] | 6.73 [2] | 6.63 [2] |
| | 2000 - 2010 | **312.3** [1] | **232.7** [1] | 261.5 [1] | 6.06 [2] | 3.04 [2] | 3.60 [2] |
| **Chloride Statistics** | | **A-31** | **A-32** | **NAS-1** | **NRMC-1** | **NRMC-2** | **NRMC-3** |
| Total Number of Chloride Samples | | 84 | 67 | 39 | 368 | 344 | 380 |
| Minimum Concentration (mg/l) | | 5.0 | 16.8 | 24.4 | 12.3 | 12.3 | 6.0 |
| Maximum Concentration (mg/l) | | 73.5 | 59.5 | 222.9 | 131.0 | 754.0 | 550.0 |
| Standard Deviation | | 12.5 | 11.0 | 56.5 | 13.1 | 83.2 | 62.8 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | NA | NA | NA | NA |
| | 1980 - 1989 | 24 | NA | NA | NA | NA | NA |
| | 1990 - 1999 | 31.8 | 24.5 | 60.7 | 24.1 | 67.6 | 42.3 |
| | 2000 - 2010 | 49.1 | 39 | **111** | 32.9 | 63.2 | 51.3 |

constitutes "special considerations". Therefore, all para-basal production wells were compared to the lower 200 gpm pump rate. Of the 18 para-basal production wells in the southern Hagåtña Basin, 13 mean decadal pump rates exceed the NGLS guideline of 200 gpm, and 11 well bottom depths exceed the NGLS guideline of -50 feet. Para-basal production well NAS-1 is situated in the northern Hagåtña Basin and should be no deeper than -50 feet and pumped less than 500 gpm. Production well NAS-1 exceeds the NGLS guideline for bottom depth, but not for mean decadal pump rate.

### Mangilao Basin

In the Mangilao Basin (Figure 14; Table 16), production is concentrated in a small area proportionate to the entire basin. The minus 40-meter volcanic basement contour is considered the boundary between the para-basal and basal groundwater zones. There are a total of 16 production wells and two test borings in the Mangilao Basin, with 10 production wells in the para-basal groundwater zone, and six production wells in the basal groundwater zone. The basal production wells include four Mangilao Golf Course production wells (MGC-1 to MGC-4) used for irrigation and two Hawaiian Rock Product production wells (HRP-1 and HRP-2) used for industrial purposes. Production well MGC-3 was abandoned in 2001.

Linear regression analysis indicates that seven production wells show significant increasing trends, NCS-3 and NCS-8 show no significant increasing trend, MGC-4 shows a significant decreasing trend, and five production wells (HRP-1, HRP-2, MGC-1, MHC-2, and M-23) show no significant decreasing trends (Appendix C). No linear regression analysis was conducted on MGC-3, which was abandoned in 2001. Chloride concentrations were highest during the 2000-10 decade than any of the previous decades in seven of the 11 production wells with more than one decade of chloride data. Also during 2000-10, mean decadal production rates were highest at all seven GWA production wells with prior production activity.

Hydraulic head measurements collected from para-basal test boring AECOM-11 in August and September 2010 exceeded 7 feet. No hydraulic head data is available for the basal groundwater zone. Six para-basal production wells exceed the NGLS bottom depth guideline of -50 feet, and no para-basal production wells exceed the NGLS pump rate guideline of 500 gpm. Pump rates at the Navy- and privately-owned production wells are reported in Mgal/month, rather than gpm, and could not be compared to NGLS guidelines. No bottom depth information

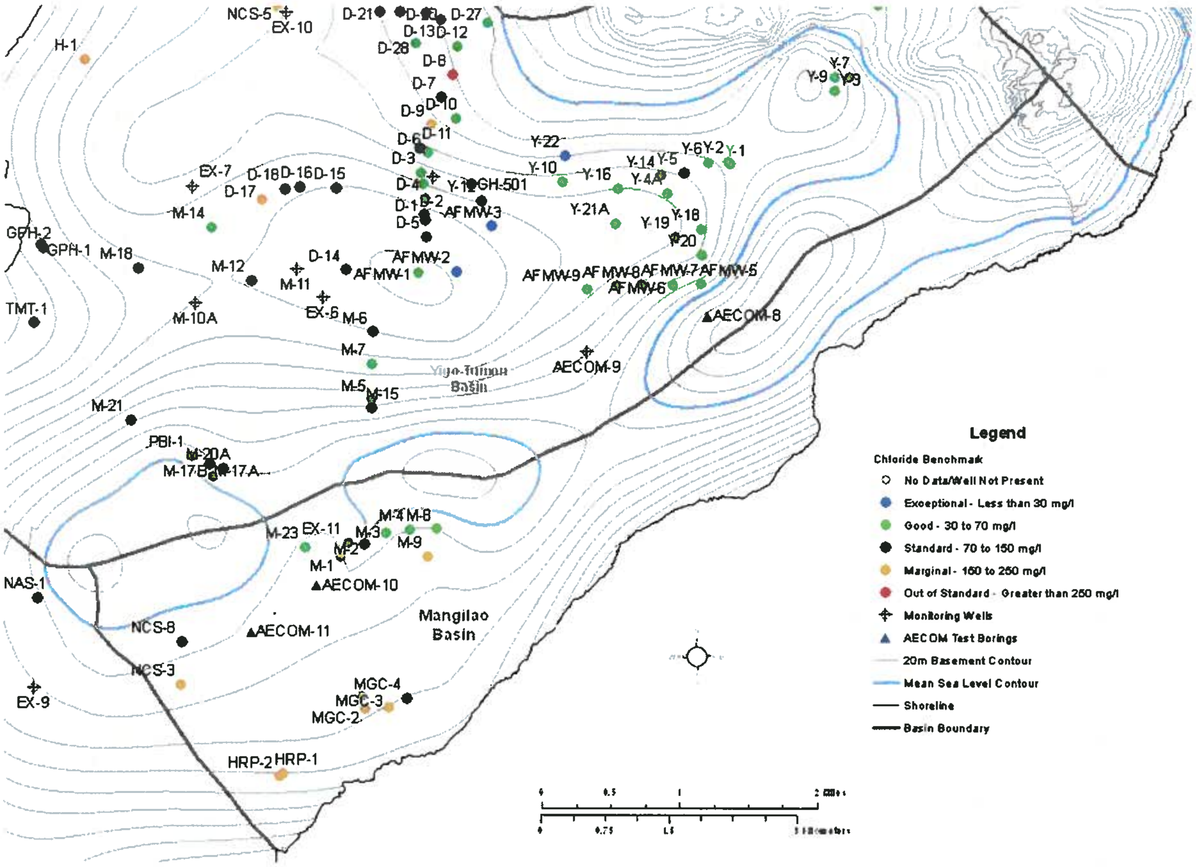


**Figure 14**: Mangilao Basin map.

**Table 16**: Mangilao Basin production well statistics.

| Production Statistics | | EX-11 | HRP-1 | HRP-2 | M-1 | M-2 | M-3 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Para-basal | Basal | Basal | Para-basal | Para-basal | Para-basal |
| Well Depth Elevation | feet | **-73.26** | -25 | -37 | -35.3 | **-59.8** | **-52.81** |
| | meters | -22.33 | -7.62 | -11.28 | -10.76 | -18.23 | -16.10 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -50 | -40 | -40 | -50 | -50 | -50 |
| Well Screen Length (feet) | | Unknown | 20 | 30 | Unknown | Unknown | 60 |
| Well Construction Year | | 1982 | 1959 | 1972 | 1965 | 1968 | 1967 |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 500 | 200 | 200 | 500 | 500 | 500 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | 183.9 [1] | NA | NA | 156.8 [1] | 145.6 [1] | 207.2 [1] |
| | 1990 - 1999 | 182.7 [1] | 3.71 [2] * | 1.39 [2] * | 126.5 [1] | 179.1 [1] | 192.5 [1] |
| | 2000 - 2010 | 202.9 [1] | 4.48 [2] * | 4 [2] * | 208.7 [1] | 191.4 [1] | 233.8 [1] |
| **Chloride Statistics** | | **EX-11** | **HRP-1** | **HRP-2** | **M-1** | **M-2** | **M-3** |
| Total Number of Chloride Samples | | 103 | 13 | 12 | 217 | 213 | 218 |
| Minimum Concentration (mg/l) | | 16.9 | 138.0 | 114.0 | 13.0 | 20.0 | 16.0 |
| Maximum Concentration (mg/l) | | 153.9 | 253.0 | 426.0 | 244.4 | 214.9 | 98.7 |
| Standard Deviation | | 20.2 | 30.8 | 78.8 | 36.8 | 33.9 | 13.4 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | NA | **140.0** | **76.3** | **25.5** |
| | 1980 - 1989 | **38.8** | **193** | **197.5** | **164.3** | **75.0** | **24.4** |
| | 1990 - 1999 | **49.1** | **194.3** | **229.2** | **183.7** | **106.7** | **28.8** |
| | 2000 - 2010 | **63.7** | **164.6** | **198.8** | **162.8** | **130.5** | **49.0** |

Note: * - Mgal/mo value obtained from annual production volume averaged over 12 months

**Table 16**: Continued.

| Production Statistics | | M-4 | M-8 | M-9 | M-23 | MGC-1 | MGC-2 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Para-basal | Para-basal | Para-basal | Para-basal | Basal | Basal |
| Well Depth Elevation | feet | -50.38 | -38.92 | -52.2 | -77 | Unknown | Unknown |
| | meters | -15.36 | -11.86 | -15.91 | -23.47 | Unknown | Unknown |
| NGLS Max. Recommended Bottom Elevation (feet) | | -50 | -50 | -50 | -50 | -40 | -40 |
| Well Screen Length (feet) | | 60 | 40 | 40 | Unknown | Unknown | Unknown |
| Well Construction Year | | 1967 | 1970 | 1970 | 1998 | Unknown | Unknown |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 500 | 500 | 500 | 500 | 200 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | 154.3 [1] | 152.3 [1] | 156.3 [1] | NA | NA | NA |
| | 1990 - 1999 | 159.7 [1] | 168.2 [1] | 156.2 [1] | NA | 2.12 [2]* | 2.04 [2]* |
| | 2000 - 2010 | 205.4 [1] | 186.6 [1] | 195.6 [1] | 254 [1] | 1.58 [2]* | 1.33 [2]* |
| **Chloride Statistics** | | **M-4** | **M-8** | **M-9** | **M-23** | **MGC-1** | **MGC-2** |
| Total Number of Chloride Samples | | 220 | 219 | 210 | 38 | 8 | 6 |
| Minimum Concentration (mg/l) | | 3.7 | 13.7 | 18.0 | 20.4 | 42.0 | 117.0 |
| Maximum Concentration (mg/l) | | 83.5 | 128.9 | 504.2 | 144.0 | 402.3 | 309.6 |
| Standard Deviation | | 11.8 | 11.8 | 69.8 | 20.1 | 129.4 | 78.1 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | 21.9 | 21.3 | 199.5 | NA | NA | NA |
| | 1980 - 1989 | 20.5 | 22.1 | 244.8 | NA | NA | NA |
| | 1990 - 1999 | 27.3 | 25.7 | 165.1 | NA | 235.8 | 208.2 |
| | 2000 - 2010 | 43.3 | 43.0 | 171.6 | 53.6 | 202.1 | 213.2 |

| Production Statistics | | MGC-3 | MGC-4 | NCS-3/3A | NCS-8 |
|---|---|---|---|---|---|
| Groundwater Zone | | Basal | Basal | Para-basal | Para-basal |
| Well Depth Elevation | feet | Unknown | Unknown | -42.1 / -36.1 | Unknown |
| | meters | Unknown | Unknown | -12.83 / -11.0 | Unknown |
| NGLS Max. Recommended Bottom Elevation (feet) | | -40 | -40 | -50 | -50 |
| Well Screen Length (feet) | | Unknown | Unknown | Unknown | Unknown |
| Well Construction Year | | Unknown | Unknown | 1993 / 2009 | Unknown |
| Status / Final Year of Production | | Abandoned 2001 | Operational | 2007 / Operational | 2002 |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 | 200 | 8.54 [2] | 7.75 [2] |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | NA | NA | 500 | 500 |
| | 1990 - 1999 | 1.57 [2]* | 2.12 [2]* | NA | NA |
| | 2000 - 2010 | 0.1 [2]* | 1.88 [2]* | 7.86 [2] | 8.69 [2] |
| **Chloride Statistics** | | **MGC-3** | **MGC-4** | **NCS-3/3A** | **NCS-8** |
| Total Number of Chloride Samples | | 5 | 9 | 289 | 171 |
| Minimum Concentration (mg/l) | | 94.0 | 48.0 | 17.9 | 38.0 |
| Maximum Concentration (mg/l) | | 459.0 | 260.0 | 335.0 | 173.0 |
| Standard Deviation | | 144.4 | 68.5 | 52.6 | 30.7 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | NA | NA |
| | 1980 - 1989 | NA | NA | NA | NA |
| | 1990 - 1999 | 214.8 | 167.7 | 151.8 | 78.6 |
| | 2000 - 2010 | 224.9 | 101.7 | 182.2 | 122.5 |

was available for NCS-8 and MGC-1 to MGC-4. Basal production wells HRP-1 and HRP-2 comply with the NGLS bottom depth guideline of -40 feet.

### Yigo-Tumon Basin

The Yigo-Tumon Basin (Figure 15; Table 17) is the largest and most productive of the six NGLA basins. There are a total of 79 production wells in the Yigo-Tumon Basin, with 67 in the basal groundwater zone, and 10 in the para-basal groundwater zone, and two in the supra-basal groundwater zone. There are seven deep monitoring wells throughout the basal zone and one test boring (AECOM-8) in the supra-basal zone.

Groundwater quality is generally "Standard" or better, with chloride concentrations exceeding 150 mg/l in only six of the 79 production wells (8%). "Exceptional" quality groundwater has occurred at 12 production wells; however, only three production wells (AFMW-2, AFMW-3, and Y-22) contained "Exceptional" quality groundwater in the 2000s. "Out of Standard" groundwater quality is only located at three production wells (D-8, D-13 and D-26), which are situated in the north-central portion of the Yigo-Tumon basin and are surrounded by many production wells that exhibit "Good" and "Standard" groundwater quality.

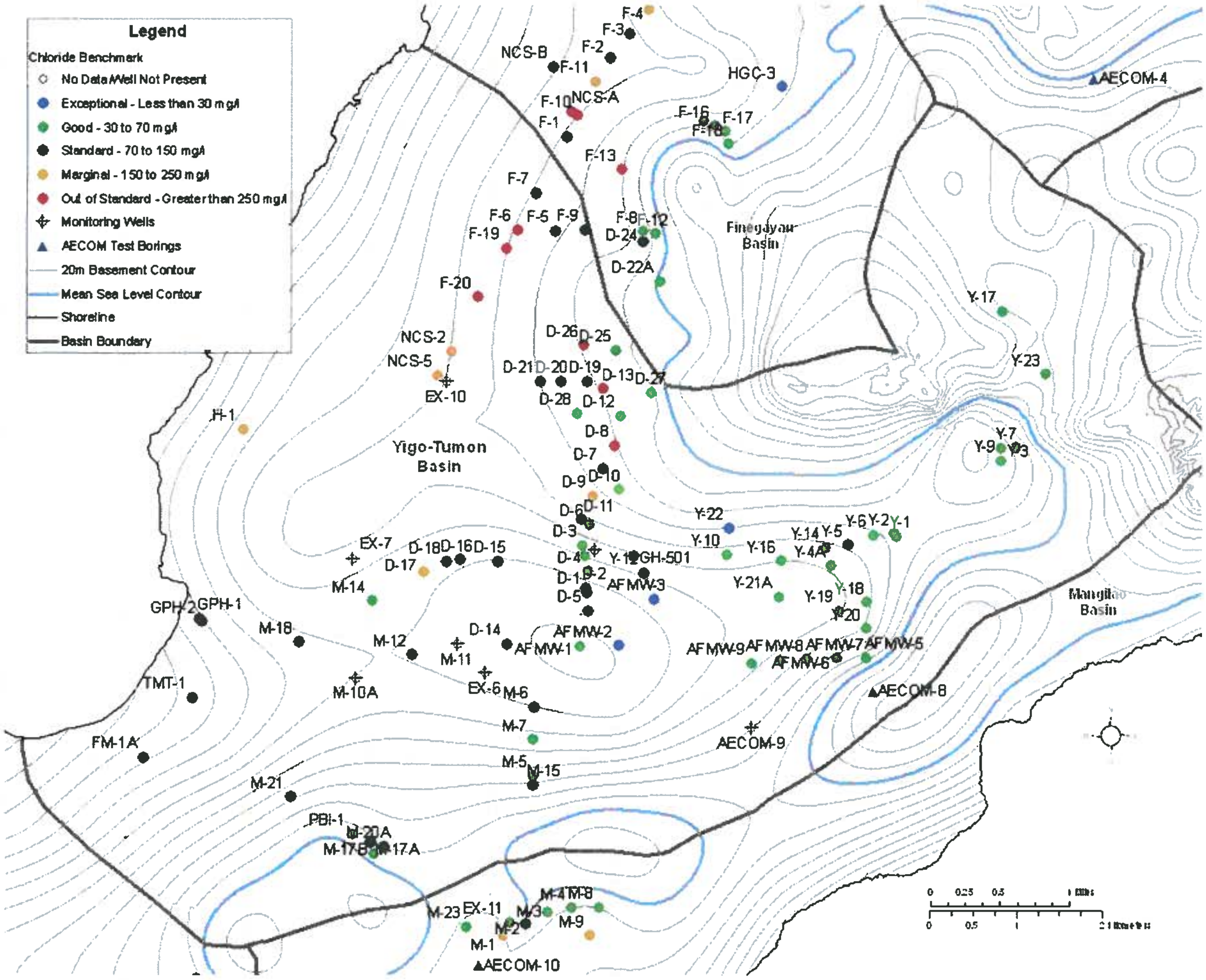


**Figure 15**: Yigo-Tumon Basin map.

**Table 17**: Yigo-Tumon Basin production well statistics.

| Production Statistics | | AFMW-1 | AFMW-2 | AFMW-3 | AFMW-5/5A | AFMW-6/6A | AFMW-7/7A |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Basal | Basal | Basal | Para-basal | Basal | Basal |
| Well Depth Elevation | feet | -41.01 | -21.61 | -22.6 | -76.5 / -35.5 | -100.13 / -35.13 | -52.16 / -43.16 |
| | meters | -12.50 | -6.59 | -6.89 | -23.32 / -10.82 | -30.52 / -10.71 | -15.9 / -13.16 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -40 | -40 | -40 | -50 | -40 | -40 |
| Well Screen Length (feet) | | Unknown | Unknown | Unknown | Unknown | Unknown | Unknown |
| Well Construction Year | | 1945 | 1945 | 1945 | 1972 / 2010 | 1965 / 2010 | 1965 / 2010 |
| Status / Final Year of Production | | Operational | 1998 | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 | 200 | 200 | 500 | 200 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | NA | NA | NA | NA | NA | NA |
| | 1990 - 1999 | 5.018 [2] | 8.791 [2] | 6.016[2] | 6.524 [2] | 14.212 [2] | 10.717 [2] |
| | 2000 - 2010 | 5.986 [2] | NA | 3.633 [2] | 6.79 [2] | 15.242 [2] | 9.681 [2] |
| **Chloride Statistics** | | **AFMW-1** | **AFMW-2** | **AFMW-3** | **AFMW-5/5A** | **AFMW-6** | **AFMW-7** |
| Total Number of Chloride Samples | | 40 | 27 | 29 | 27 | 25 | 30 |
| Minimum Concentration (mg/l) | | 34.3 | 13.8 | 22.2 | 37.0 | 42.6 | 34.7 |
| Maximum Concentration (mg/l) | | 67.0 | 67.2 | 38.0 | 67.0 | 72.6 | 60.0 |
| Standard Deviation | | 9.3 | 16.0 | 3.5 | 6.3 | 8.8 | 5.8 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | NA | NA | NA | NA |
| | 1980 - 1989 | 44 | 33 | 27.7 | 47.3 | 51.8 | 41.7 |
| | 1990 - 1999 | 47.9 | 51.9 | 28.9 | 50 | 60.9 | 45.1 |
| | 2000 - 2010 | 50 | 17.1 | 25.1 | 46.5 | 66.1 | 43.2 |

**Table 17**: Continued.

| Production Statistics | | AFMW-8/8A | AFMW-9/9A | D-1 | D-2 | D-3 | D-4 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Basal | Basal | Basal | Basal | Basal | Basal |
| Well Depth Elevation | feet | -26.75 / -38.75 | -26.79 / -36.79 | -38.1 | -35.17 | -23.34 | -24.5 |
| | meters | -8.15 / -11.81 | -8.17 / -11.21 | -11.61 | -10.72 | -7.11 | -7.47 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -40 | -40 | -40 | -40 | -40 | -40 |
| Well Screen Length (feet) | | Unknown | Unknown | 35 | 35 | 35 | 25 |
| Well Construction Year | | 1965 / 2010 | 1965 / 2010 | 1973 | 1973 | 1973 | 1973 |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | 2002 | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 | 200 | 200 | 200 | 200 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | NA | NA | 177.2 [1] | 183.3 [1] | 140.3 [1] | 154.5 [1] |
| | 1990 - 1999 | 15.034 [2] | 14.445 [2] | **212** [1] | 199.3 [1] | 161.6 [1] | 151.6 [1] |
| | 2000 - 2010 | 16.628 [2] | 13.929 [2] | **229** [1] | **206.7** [1] | NA | **261** [1] |
| **Chloride Statistics** | | **AFMW-8/8A** | **AFMW-9/9A** | **D-1** | **D-2** | **D-3** | **D-4** |
| Total Number of Chloride Samples | | 24 | 36 | 221 | 215 | 185 | 214 |
| Minimum Concentration (mg/l) | | 28.0 | 27.0 | 24.0 | 24.0 | 22.1 | 22.0 |
| Maximum Concentration (mg/l) | | 70.8 | 79.3 | 143.9 | 109.6 | 65.5 | 86.2 |
| Standard Deviation | | 8.7 | 8.1 | 13.0 | 12.1 | 6.2 | 10.0 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | 55.2 | 55.2 | 35.5 | 38.8 |
| | 1980 - 1989 | 41.7 | 41.9 | 58.9 | 61.8 | 37 | 43.6 |
| | 1990 - 1999 | 48.4 | 46.4 | 64 | 62.5 | 38.3 | 41.4 |
| | 2000 - 2010 | 41.6 | 53.9 | **74.6** | **74.1** | 45.1 | 59.3 |

| Production Statistics | | D-5 | D-6 | D-7 | D-8 | D-9 | D-10 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Basal | Basal | Basal | Basal | Basal | Basal |
| Well Depth Elevation | feet | -31.81 | -26.29 | **-48.98** | -35.68 | -27.52 | -25.09 |
| | meters | -9.70 | -8.01 | -14.93 | -10.88 | -8.39 | -7.65 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -40 | -40 | -40 | -40 | -40 | -40 |
| Well Screen Length (feet) | | 40 | 40 | 60 | 40 | 35 | 35 |
| Well Construction Year | | 1973 | 1973 | 1973 | 1973 | 1973 | 1973 |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 | 200 | 200 | 200 | 200 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | 133.6 [1] | 161.1 [1] | 147.1 [1] | 136.7 [1] | 168.2 [1] | 161.2 [1] |
| | 1990 - 1999 | 173.5 [1] | **205.3** [1] | 193.6 [1] | 192.6 [1] | 189.8 [1] | 195.7 [1] |
| | 2000 - 2010 | 163.4 [1] | **270.9** [1] | **228** [1] | 181.1 [1] | **223.7** [1] | **234.6** [1] |
| **Chloride Statistics** | | **D-5** | **D-6** | **D-7** | **D-8** | **D-9** | **D-10** |
| Total Number of Chloride Samples | | 222 | 215 | 221 | 220 | 213 | 220 |
| Minimum Concentration (mg/l) | | 34.0 | 29.1 | 29.8 | 55.0 | 11.2 | 26.3 |
| Maximum Concentration (mg/l) | | 95.8 | 100.0 | 234.0 | 531.9 | 289.0 | 100.5 |
| Standard Deviation | | 10.2 | 12.4 | 18.3 | 80.1 | 37.1 | 12.6 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | 59.2 | 51.2 | 50.8 | **135.1** | **110.5** | 38.6 |
| | 1980 - 1989 | 63.4 | 50.5 | 52.2 | 170.2 | **131.8** | 39.7 |
| | 1990 - 1999 | 58.1 | 56.3 | 58.3 | 227.7 | 156.7 | 41.9 |
| | 2000 - 2010 | **71.8** | 68.7 | **82.1** | 283.7 | 180.4 | 62.8 |

| Production Statistics | | D-11 | D-12 | D-13 | D-14 | D-15 | D-16 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Basal | Para-basal | Para-basal | Basal | Basal | Basal |
| Well Depth Elevation | feet | -37 | -48.2 | **-50.88** | **-55.75** | **-93.12** | **-58.4** |
| | meters | -11.28 | -14.69 | -15.51 | -16.99 | -28.38 | -17.80 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -40 | -50 | -50 | -40 | -40 | -40 |
| Well Screen Length (feet) | | 50 | 50 | 40 | 40 | 40 | 40 |
| Well Construction Year | | 1973 | 1973 | 1974 | 1973 | 1974 | 1979 |
| Status / Final Year of Production | | Operational | Operational | 2009 | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 | 500 | 500 | 200 | 200 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | 165.1 [1] | 144.9 [1] | 149.4 [1] | 166.6 [1] | 161.2 [1] | 189.3 [1] |
| | 1990 - 1999 | **222.9** [1] | 171.9 [1] | 162.9 [1] | 197.3 [1] | **204.3** [1] | 197.4 [1] |
| | 2000 - 2010 | 192.2 [1] | 220.2 [1] | 181.4 [1] | **258** [1] | **244.5** [1] | **231.3** [1] |
| **Chloride Statistics** | | **D-11** | **D-12** | **D-13** | **D-14** | **D-15** | **D-16** |
| Total Number of Chloride Samples | | 215 | 218 | 200 | 215 | 197 | 150 |
| Minimum Concentration (mg/l) | | 34.4 | 6.0 | 39.0 | 21.8 | 51.0 | 54.0 |
| Maximum Concentration (mg/l) | | 214.0 | 172.0 | 917.3 | 135.0 | 193.6 | 146.4 |
| Standard Deviation | | 19.8 | 14.4 | 176.1 | 24.1 | 18.0 | 16.1 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | **82.4** | 18.2 | 275.5 | 33.2 | **80.3** | **78.1** |
| | 1980 - 1989 | **73.6** | 20.9 | 242.3 | 41.7 | **86.7** | **78.7** |
| | 1990 - 1999 | **94.4** | 26.4 | 308.3 | 61.6 | **96.6** | **87.6** |
| | 2000 - 2010 | **90** | 36.8 | 518.1 | **89** | **97.5** | **97.5** |

**Table 17**: Continued.

| Production Statistics | | D-17 | D-18 | D-19 | D-20 | D-21 | D-25 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Basal | Basal | Basal | Basal | Basal | Para-basal |
| Well Depth Elevation | feet | -35.6 | -59.63 | -49.84 | -50.23 | -56.93 | -85.2 |
| | meters | -10.85 | -18.18 | -15.19 | -15.31 | -17.35 | -25.97 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -40 | -40 | -40 | -40 | -40 | -50 |
| Well Screen Length (feet) | | 35 | Unknown | Unknown | Unknown | Unknown | Unknown |
| Well Construction Year | | 1979 | 1980 | 1984 | 1984 | 1984 | 2004 |
| Status / Final Year of Production | | 2002 | 2000 | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 | 200 | 200 | 200 | 200 | 500 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | 149 [1] | 177.6 [1] | 204.4 [1] | 223.3 [1] | 179.7 [1] | NA |
| | 1990 - 1999 | 197.6 [1] | 187.5 [1] | 200.1 [1] | 189.9 [1] | 155.4 [1] | NA |
| | 2000 - 2010 | NA | NA | 203.9 [1] | 216.1 [1] | 198.2 [1] | 344.1 [1] |
| Chloride Statistics | | D-17 | D-18 | D-19 | D-20 | D-21 | D-25 |
| Total Number of Chloride Samples | | 119 | 98 | 103 | 105 | 103 | 27 |
| Minimum Concentration (mg/l) | | 15.9 | 35.5 | 14.4 | 42.0 | 32.0 | 23.6 |
| Maximum Concentration (mg/l) | | 280.0 | 204.0 | 118.0 | 111.0 | 129.0 | 85.2 |
| Standard Deviation | | 74.1 | 20.6 | 15.2 | 17.7 | 16.6 | 14.6 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | 22.6 | NA | NA | NA | NA | NA |
| | 1980 - 1989 | 60.7 | 70.9 | 66.6 | 59.5 | 72.6 | NA |
| | 1990 - 1999 | 182.6 | 86 | 63.8 | 60.6 | 73.2 | NA |
| | 2000 - 2010 | 171.2 | 82.5 | 78.2 | 89 | 92.3 | 51.5 |

| Production Statistics | | D-26 | D-27 | D-28 | EX-5A | F-5 | F-6 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Para-basal | Para-basal | Basal | Basal | Basal | Basal |
| Well Depth Elevation | feet | -44.81 | -64.33 | -47.92 | -39.81 | -35.65 | -24.58 |
| | meters | -13.66 | -19.61 | -14.61 | -12.13 | -10.87 | -7.49 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -50 | -50 | -40 | -40 | -40 | -40 |
| Well Screen Length (feet) | | Unknown | Unknown | Unknown | Unknown | 40 | 30 |
| Well Construction Year | | 2004 | 2004 | 2004 | 1985 | 1975 | 1975 |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 500 | 500 | 200 | 200 | 200 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | NA | NA | NA | 208.3 [1] | 132.6 [1] | 124.2 [1] |
| | 1990 - 1999 | NA | NA | NA | 214.6 [1] | 154.1 [1] | 159 [1] |
| | 2000 - 2010 | 217.5 [1] | 348.6 [1] | 170.1 [1] | 361.9 [1] | 196.1 [1] | 218.8 [1] |
| Chloride Statistics | | D-26 | D-27 | D-28 | EX-5A | F-5 | F-6 |
| Total Number of Chloride Samples | | 24 | 26 | 27 | 101 | 192 | 188 |
| Minimum Concentration (mg/l) | | 141.0 | 16.3 | 25.5 | 24.0 | 23.8 | 32.0 |
| Maximum Concentration (mg/l) | | 387.8 | 68.2 | 97.0 | 82.0 | 334.0 | 604.6 |
| Standard Deviation | | 80.3 | 13.0 | 16.3 | 12.5 | 42.2 | 113.1 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | NA | NA | 51.4 | 124.3 |
| | 1980 - 1989 | NA | NA | NA | 38.8 | 64.8 | 173 |
| | 1990 - 1999 | NA | NA | NA | 42.3 | 92.4 | 204.9 |
| | 2000 - 2010 | 256.8 | 32.9 | 65 | 59.4 | 139.9 | 359.9 |

| Production Statistics | | F-7 | F-9 | F-19 | F-20 | FM-1/1A | GH-501 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Basal | Basal | Basal | Basal | Basal | Basal |
| Well Depth Elevation | feet | -24.16 | -49.37 | -46 | -63.5 | Unknown / -5.87 | -46.95 |
| | meters | -7.36 | -15.05 | -14.02 | -19.35 | Unknown / -1.79 | -14.31 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -40 | -40 | -40 | -40 | -40 | -40 |
| Well Screen Length (feet) | | 70 | 50 | Unknown | Unknown | Unknown / 22 | Unknown |
| Well Construction Year | | 1975 | 1978 | 1996 | 1996 | 1961 / 1997 | 1983 |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 | 200 | 200 | 200 | 200 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | 128.5 [1] | 163.4 [1] | NA | NA | NA | 168.9 [1] |
| | 1990 - 1999 | 175.5 [1] | 138.2 [1] | NA | NA | 2.7 [2] * | 176.9 [1] |
| | 2000 - 2010 | 185 [1] | 154.5 [1] | 188.7 [1] | 186.6 [1] | 1.96 [2] * | 163.8 [1] |
| Chloride Statistics | | F-7 | F-9 | F-19 | F-20 | FM-1/1A | GH-501 |
| Total Number of Chloride Samples | | 194 | 155 | 24 | 27 | 13 | 105 |
| Minimum Concentration (mg/l) | | 18.9 | 38.0 | 152.9 | 149.4 | 101.0 | 34.0 |
| Maximum Concentration (mg/l) | | 246.4 | 199.9 | 405.8 | 466.3 | 166.0 | 299.9 |
| Standard Deviation | | 35.0 | 25.5 | 69.0 | 87.1 | 20.4 | 46.7 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | 53.2 | 74 | NA | NA | NA | NA |
| | 1980 - 1989 | 66.1 | 64.5 | NA | NA | 122.3 | 76.6 |
| | 1990 - 1999 | 85 | 59.7 | NA | NA | 126 | 86.9 |
| | 2000 - 2010 | 131.2 | 96.2 | 251.9 | 278.8 | 122.3 | 147.7 |

Note: * - Mgal/mo value obtained from annual production volume averaged over 12 months

**Table 17**: Continued.

| Production Statistics | | GPH-1 | GPH-2 | H-1 | M-5 | M-6 | M-7 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Basal | Basal | Basal | Basal | Basal | Basal |
| Well Depth Elevation | feet | Unknown | Unknown | **-50.05** | **-92.09** | **-85.93** | **-55.34** |
| | meters | Unknown | Unknown | -15.26 | -28.07 | -26.19 | -16.87 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -40 | -40 | -40 | -40 | -40 | -40 |
| Well Screen Length (feet) | | Unknown | Unknown | Unknown | 70 | 85 | 50 |
| Well Construction Year | | Unknown | Unknown | 1945 | 1973 | 1973 | 1973 |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 | 200 | 200 | 200 | 200 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | NA | NA | 178.8 [1] | 149.4 [1] | 131.7 [1] | 180.8 [1] |
| | 1990 - 1999 | 1.6 [2] * | NA | **246.8** [1] | 163.7 [1] | 188.6 [1] | 172.2 [1] |
| | 2000 - 2010 | 1.28 [2] * | 1.47 [2] * | **285.4** [1] | **217.8** [1] | **209.2** [1] | **210.1** [1] |
| **Chloride Statistics** | | **GPH-1** | **GPH-2** | **H-1** | **M-5** | **M-6** | **M-7** |
| Total Number of Chloride Samples | | 4 | 3 | 183 | 214 | 213 | 207 |
| Minimum Concentration (mg/l) | | 76.6 | 78.0 | 52.3 | 14.0 | 16.0 | 3.5 |
| Maximum Concentration (mg/l) | | 87.3 | 84.8 | 221.4 | 97.0 | 252.9 | 90.0 |
| Standard Deviation | | 4.8 | 3.6 | 41.2 | 14.7 | 46.2 | 11.0 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | **76.6** | 39.1 | 63.3 | 33 |
| | 1980 - 1989 | NA | NA | **113.1** | 47.2 | 63.7 | 38 |
| | 1990 - 1999 | NA | NA | **129.8** | 54.7 | **80.5** | 41.5 |
| | 2000 - 2010 | **83.3** | **80.7** | 173.6 | 68.2 | **131.1** | 54.9 |

| Production Statistics | | M-12 | M-14 | M-15 | M-17A | M-17B | M-18 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Basal | Basal | Basal | Para-basal | Para-basal | Basal |
| Well Depth Elevation | feet | **-53.11** | **-40.98** | **-51.21** | **-54.49** | -41.28 | **-40.36** |
| | meters | -16.19 | -12.49 | -15.61 | -16.61 | -12.58 | -12.30 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -40 | -40 | -40 | -50 | -50 | -40 |
| Well Screen Length (feet) | | 60 | 40 | 40 | Unknown | 40 | Unknown |
| Well Construction Year | | 1973 | 1974 | 1983 | 1990 | 1990 | 1997 |
| Status / Final Year of Production | | Operational | 2005 | Operational | 2002 | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 | 200 | 200 | 500 | 500 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | 105.4 [1] | 176.3 [1] | 174.8 [1] | NA | NA | NA |
| | 1990 - 1999 | 103.8 [1] | **225.1** [1] | 190.2 [1] | 198.6 [1] | 288.2 [1] | **371.6** [1] |
| | 2000 - 2010 | 110.1 [1] | 159.2 [1] | **246** [1] | NA | 285.8 [1] | **273.8** [1] |
| **Chloride Statistics** | | **M-12** | **M-14** | **M-15** | **M-17A** | **M-17B** | **M-18** |
| Total Number of Chloride Samples | | 179 | 176 | 115 | 46 | 80 | 51 |
| Minimum Concentration (mg/l) | | 16.0 | 14.1 | 21.0 | 23.0 | 11.1 | 40.0 |
| Maximum Concentration (mg/l) | | 251.9 | 127.1 | 159.4 | 116.0 | 96.0 | 114.0 |
| Standard Deviation | | 30.9 | 19.6 | 28.4 | 21.2 | 15.7 | 15.3 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | 65.5 | 35.2 | NA | NA | NA | NA |
| | 1980 - 1989 | **79.1** | 38.2 | 43.9 | NA | NA | NA |
| | 1990 - 1999 | **92** | 51.8 | 47.3 | **71.2** | 61.5 | 56.6 |
| | 2000 - 2010 | **116.3** | 47.4 | **75.8** | **89.6** | 68.6 | **71.5** |

| Production Statistics | | M-20A | M-21 | NCS-2/2A | NCS-5 | PBI-1 | TMT-1 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Para-basal | Basal | Basal | Basal | Para-basal | Basal |
| Well Depth Elevation | feet | -21.4 | -34.85 | **-46 / -58.2** | Unknown | **-71.33** | NA |
| | meters | -6.52 | -10.62 | -14.02 / -17.74 | Unknown | -21.74 | NA |
| NGLS Max. Recommended Bottom Elevation (feet) | | -50 | -40 | -40 | -40 | -50 | NA |
| Well Screen Length (feet) | | Unknown | Unknown | Unknown | Unknown | Unknown | NA |
| Well Construction Year | | 1996 | 1998 | 1980 / 1995 | Unknown | 1993 | 1947 |
| Status / Final Year of Production | | Operational | Operational | 2001 | 2006 | Operational | 1995 |
| NGLS Max. Recommended Pump Rate (gpm) | | 500 | 200 | 200 | 200 | 500 | NA |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | NA | NA | NA | NA | NA | NA |
| | 1990 - 1999 | 257.8 [1] | NA | 7.857 [2] | 3.772 [2] | 1.25 [2] * | 32.991 [2] |
| | 2000 - 2010 | 259.5 [1] | **298.1** [1] | 8.543 [2] | 3.089 [2] | 0.59 [2] * | NA |
| **Chloride Statistics** | | **M-20A** | **M-21** | **NCS-2/2A** | **NCS-5** | **PBI-1** | **TMT-1** |
| Total Number of Chloride Samples | | 55 | 43 | 210 | 328 | 9 | 31 |
| Minimum Concentration (mg/l) | | 43.3 | 45.0 | 31.0 | 25.5 | 50.3 | 15.0 |
| Maximum Concentration (mg/l) | | 151.4 | 181.3 | 309.0 | 483.0 | 122.0 | 103.0 |
| Standard Deviation | | 23.5 | 32.3 | 34.1 | 102.5 | 20.5 | 15.6 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | NA | NA | NA | NA |
| | 1980 - 1989 | NA | NA | NA | NA | NA | **81.2** |
| | 1990 - 1999 | 69.2 | 63.7 | **130.6** | 240.6 | **85.5** | **77.7** |
| | 2000 - 2010 | **82.1** | **110.6** | 193.2 | 164.9 | 66.9 | **81.3** |

**Table 17**: Continued.

| Production Statistics | | Y-1 | Y-2 | Y-3 | Y-4/4A | Y-5 | Y-6 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Basal | Basal | Basal | Basal | Basal | Basal |
| Well Depth Elevation | feet | -35.16 | **-52.17** | -25.39 | **-46.5 / -52.97** | **-47.4** | **-47.27** |
| | meters | -10.72 | -15.90 | -7.74 | -14.17 / -16.15 | -14.45 | -14.41 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -40 | -40 | -40 | -40 | -40 | -40 |
| Well Screen Length (feet) | | 40 | 70 | Unknown | 40 / Unknown | 35 | Unknown |
| Well Construction Year | | 1973 | 1973 | 1973 | 1974 / 1994 | 1979 | 1980 |
| Status / Final Year of Production | | Operational | Operational | Operational | 1994 / Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 | 200 | 200 | 200 | 200 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | 142.2 [1] | 158.3 [1] | 118 [1] | 127.1 [1] | 150.1 [1] | 140.9 [1] |
| | 1990 - 1999 | 134.7 [1] | 157 [1] | 154.5 [1] | 141.4 [1] | 147.2 [1] | 157.9 [1] |
| | 2000 - 2010 | 195 [1] | 194.8 [1] | **205.8** [1] | **222.6** [1] | 191.1 [1] | **233.9** [1] |
| **Chloride Statistics** | | **Y-1** | **Y-2** | **Y-3** | **Y-4/4A** | **Y-5** | **Y-6** |
| Total Number of Chloride Samples | | 220 | 218 | 216 | 176 | 157 | 142 |
| Minimum Concentration (mg/l) | | 12.8 | 12.8 | 10.0 | 12.8 | 16.0 | 12.0 |
| Maximum Concentration (mg/l) | | 64.8 | 94.0 | 59.6 | 69.2 | 106.6 | 62.5 |
| Standard Deviation | | 8.2 | 9.6 | 8.9 | 8.7 | 19.2 | 9.7 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | 18.6 | 18.6 | 17.4 | 20.6 | 30.9 | NA |
| | 1980 - 1989 | 23.1 | 24 | 21.8 | 24.8 | 36 | 21.9 |
| | 1990 - 1999 | 24 | 25.1 | 22.7 | 29.3 | 46.5 | 23.6 |
| | 2000 - 2010 | 34.3 | 37.2 | 35 | 39.4 | **73.8** | 36.1 |

| Production Statistics | | Y-7 | Y-9 | Y-10 | Y-12 | Y-14 | Y-16 |
|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Basal | Basal | Basal | Basal | Basal | Basal |
| Well Depth Elevation | feet | -30.7 | **-50.57** | **-54.99** | **-40.91** | -37.78 | **-41.06** |
| | meters | -9.36 | -15.41 | -16.76 | -12.47 | -11.52 | -12.52 |
| NGLS Max. Recommended Bottom Elevation (feet) | | -40 | -40 | -40 | -40 | -40 | -40 |
| Well Screen Length (feet) | | 30 | Unknown | Unknown | Unknown | Unknown | Unknown |
| Well Construction Year | | 1983 | 1988 | 1997 | 1996 | 1998 | 2001 |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | 200 | 200 | 200 | 200 | 200 | 200 |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | **361.2** [1] | **422** [1] | NA | NA | NA | NA |
| | 1990 - 1999 | **339.3** [1] | **317.9** [1] | 181.7 [1] | **280.3** [1] | **250** [1] | NA |
| | 2000 - 2010 | **277.4** [1] | **464.6** [1] | **234.7** [1] | **317.9** [1] | **330.3** [1] | **297.2** [1] |
| **Chloride Statistics** | | **Y-7** | **Y-9** | **Y-10** | **Y-12** | **Y-14** | **Y-16** |
| Total Number of Chloride Samples | | 84 | 89 | 46 | 55 | 17 | 38 |
| Minimum Concentration (mg/l) | | 14.0 | 6.7 | 27.0 | 33.0 | 32.0 | 13.9 |
| Maximum Concentration (mg/l) | | 49.0 | 51.0 | 78.7 | 110.1 | 71.0 | 71.2 |
| Standard Deviation | | 6.0 | 9.7 | 13.5 | 14.3 | 11.2 | 10.9 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | NA | NA | NA | NA |
| | 1980 - 1989 | 22.5 | 21 | NA | NA | NA | NA |
| | 1990 - 1999 | 23.2 | 21.7 | 36.4 | 55.1 | 44 | NA |
| | 2000 - 2010 | 34 | 36 | 58.5 | **71.8** | 55.5 | 46.9 |

| Production Statistics | | Y-17 | Y-18 | Y-19 | Y-20 | Y-21A | Y-22 | Y-23 |
|---|---|---|---|---|---|---|---|---|
| Groundwater Zone | | Supra-basal | Basal | Basal | Basal | Basal | Basal | Supra-basal |
| Well Depth Elevation | feet | 194.13 | **-46.37** | **-41.7** | **-45.04** | -37.06 | **-57.31** | 87.25 |
| | meters | 59.17 | -14.13 | -12.71 | -13.73 | -11.30 | -17.47 | 26.59 |
| NGLS Max. Recommended Bottom Elevation (feet) | | NA | -40 | -40 | -40 | -40 | -40 | NA |
| Well Screen Length (feet) | | Unknown | 40 | 40 | 40 | Unknown | Unknown | Unknown |
| Well Construction Year | | 2002 | 2004 | 2004 | 2004 | 2001 | 2004 | 2002 |
| Status / Final Year of Production | | Operational | Operational | Operational | Operational | Operational | Operational | Operational |
| NGLS Max. Recommended Pump Rate (gpm) | | NA | 200 | 200 | 200 | 200 | 200 | NA |
| Mean Pump Rate (gpm)[1] (Mgal/month)[2] | 1980 - 1989 | NA | NA | NA | NA | NA | NA | NA |
| | 1990 - 1999 | NA | NA | NA | NA | NA | NA | NA |
| | 2000 - 2010 | 359.1 [1] | **221** [1] | **416.1** [1] | **514.8** [1] | **211.1** [1] | **240.1** [1] | 298.4 [1] |
| **Chloride Statistics** | | **Y-17** | **Y-18** | **Y-19** | **Y-20** | **Y-21A** | **Y-22** | **Y-23** |
| Total Number of Chloride Samples | | 33 | 25 | 27 | 26 | 37 | 26 | 34 |
| Minimum Concentration (mg/l) | | 24.4 | 24.0 | 26.6 | 21.0 | 19.4 | 18.7 | 19.4 |
| Maximum Concentration (mg/l) | | 73.5 | 64.0 | 69.2 | 63.5 | 93.6 | 39.5 | 61.3 |
| Standard Deviation | | 8.7 | 10.7 | 11.9 | 11.7 | 15.1 | 7.5 | 8.9 |
| Mean Chloride Concentration (mg/l) | 1973 - 1979 | NA | NA | NA | NA | NA | NA | NA |
| | 1980 - 1989 | NA | NA | NA | NA | NA | NA | NA |
| | 1990 - 1999 | NA | NA | NA | NA | NA | NA | NA |
| | 2000 - 2010 | 36.9 | 37.1 | 46.3 | 41.7 | 53.6 | 29.3 | 41.1 |

Linear regression analysis indicates that 59 production wells show a significant increasing trend, 13 production wells show no significant increasing trend, NCS-5 shows a significant decreasing trend, and six production wells show no significant decreasing trend (Appendix C). Chloride concentrations were higher during the 2000-10 decade than any of the previous decades in 51 of the 62 production wells (82%) with more than one decade of Linear regression analysis indicates that 59 production wells show a significant increasing trend, 13 production wells show no significant increasing trend, NCS-5 shows a significant decreasing trend, and six production wells show no significant decreasing trend chloride data. The 2000-10 mean decadal production rates were highest at 37 of those 51 production wells (73%).

Based on historical groundwater levels and specific conductance data in the Yigo-Tumon Basin, the boundary between the para-basal and basal groundwater zones, or the saltwater toe, is located along the volcanic basement between about -15 and -58 meters (-49 and -190 feet). To categorize the basal and para-basal production wells for this study, the -40 meter volcanic basement contour was chosen as the saltwater toe boundary.

Hydraulic head measurements at monitoring wells EX-6, EX-7, EX-10, GHURA-DEDEDO, M-10A, and M-11, all situated in basal groundwater zones, range from 1.3 to 8.3 feet. Given that hydraulic head measurements have been less than 4 feet at all six monitoring wells, production wells in the Yigo-Tumon Basin were compared to the more conservative well design guidelines of -40-foot depth and 200 gpm pump rate. Pump rates at the Navy- and privately-owned production wells are reported in Mgal/month, rather than gpm, and could not be compared to NGLS guidelines.

The NGLS well design guidelines allow deeper wells with higher pumping rates for the "upper Yigo sub-basin", but the boundaries for that specific area were not defined in the NGLS. If the minus 40-meter contour is carried across the entire Yigo-Tumon Basin, three Y-series production wells (Y-3, Y-7, and Y-9), situated in the uppermost Yigo-Tumon Basin, are located in the basal groundwater zone. No well design guidelines exist for supra-basal production wells Y-17 and Y-23 or the horizontal Maui-type well TMT-1. Although TMT-1 has not operated since 1995, chloride concentrations collected semi-annually since 2005 exhibit "Good" groundwater quality.

Of the 10 para-basal production wells, six exceed the NGLS bottom depth guideline of -50 feet, and none exceed the NGLS pump rate guideline of 500 gpm. Of the 67 basal production wells, 37 exceed the NGLS bottom depth guideline of -40 feet, and 37 exceed the NGLS pump rate guideline of 200 gpm; no well construction information was available for NCS-5.

## 5.3 Analysis of Chloride Data with Hydrologic Variables

This section discusses general observations made from comparing the chloride trends at production wells to existing hydrologic datasets, such as rainfall, MSL, and the SOI, to better understand the contribution of these selected variables to salinity conditions within the aquifer and within each groundwater zone. Graphs illustrating the chloride and production trends for all the production wells are provided in Appendix F.

### Chloride Trends According to Groundwater Zone

There is no single chloride trend that typifies the basal, para-basal, or supra-basal groundwater zones, or the NGLA as an aquifer. The heterogeneity of the NGLA, as well as the unique construction and management of the 154 production wells, is revealed in the heterogeneity of the chloride trends. Only a handful of the NGLA production wells are used to discuss the groundwater zones and hydrologic variables; they were selected to highlight specific observations and insights into the aquifer.

Basal Groundwater

A total of 100 production wells across the NGLA are located in a basal groundwater zone. Chloride concentrations exhibit a cyclical increasing trend at many production wells in basal groundwater zones in the Finegayan, Hagåtña and Yigo-Tumon Basins. Production well M-6, located in the Yigo-Tumon Basin, is one of the best examples of the observed cyclical chloride trend (Figure 16). At M-6, the magnitude of the peaks and troughs increase with each new cycle, which has a period of approximately 4-6 years. During the last cycle, which started around 2005, chloride concentrations continue to increase despite decreasing pump rates. Production well A-10, located in the Hagåtña Basin (Figure 17), exhibits a cyclical trend in the 1970s, but in subsequent decades the chloride concentrations at A-10 become more variable and the cyclical trend is less distinguishable. The cyclical trend appears much shorter at A-10 than M-6, with a period of approximately 1-2 years in the 1970s. Both production wells are situated centrally within their basins where the freshwater lens is relatively thick and the underlying volcanic basement is approximately 100 meters (328 feet) deeper than their termination depths.

Production wells F-10 in the Finegayan Basin (Figure 18) is a good example of how the chloride trends remain un-affected by production rates. Despite relatively stable production rates, the cyclical chloride trend at F-10 occurs with a periodicity of 4-7 years. Additionally, the magnitudes of each peak have increased with each cycle. At the peak in 1980, the chloride concentration was below the 250 mg/l drinking water standard, but the peak in 2009 exceeds 425 mg/l. Chloride concentrations in the troughs have remained below the drinking water standard with each cycle.

Para-basal Groundwater

A total of 50 production wells across the NGLA are located in a para-basal groundwater zone. Although the freshwater lens rests upon the volcanic basement, the groundwater in the para-basal zone is susceptible to increased salinity if the saltwater toe migrates inland. This increase usually occurs with periods of reduced recharge or sea level rise. Also, a production

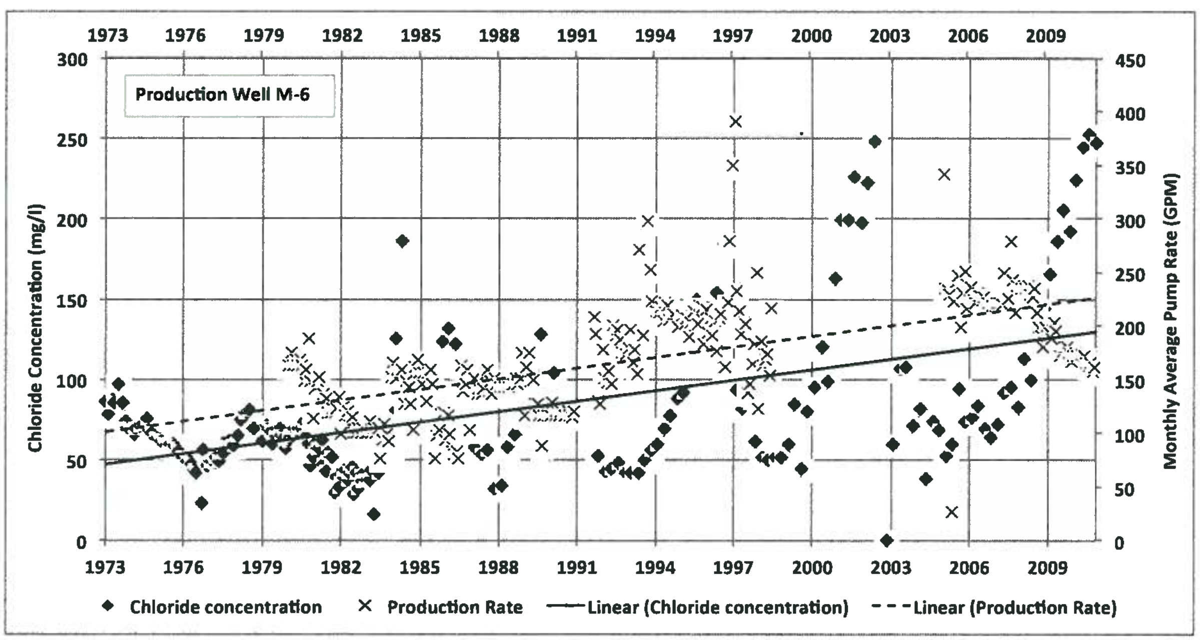


**Figure 16**: Chloride and production trends at production well M-6 in the Yigo-Tumon Basin.

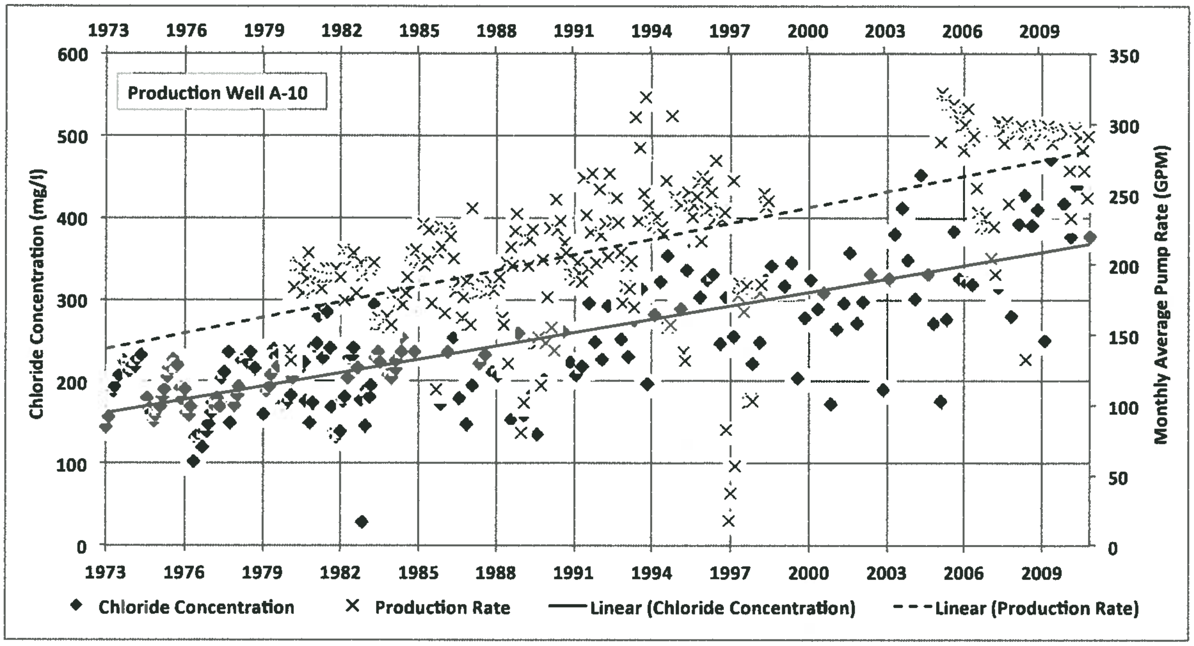


**Figure 17**: Chloride and production trends at production well A-10 in the Hagåtña Basin.

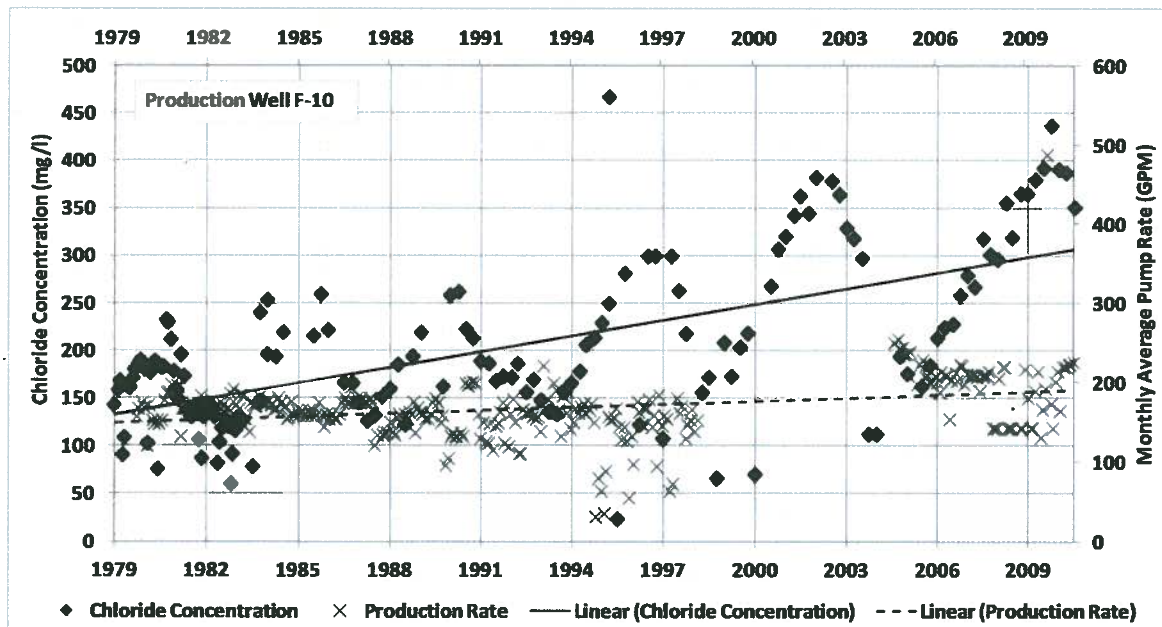


**Figure 18**: Chloride and production trends at production wells F-10 in the Finegayan Basin.

well's status as a para-basal or basal well may change depending on the position of the Saltwater toe. Other potential causes of increased salinity include a hydraulic connection between the well and higher salinity groundwater in the basal zone through intersected fractures or conduits. Even if the production wells are not hydraulically connected to higher salinity groundwater, dissolved salts still infiltrate into the groundwater from rainfall and other terrestrial sources.

Production well D-13 (Figure 19), in the Yigo-Tumon Basin, is categorized as a basal well but is situated near the basal/para-basal boundary or the saltwater toe. D-13 is a good

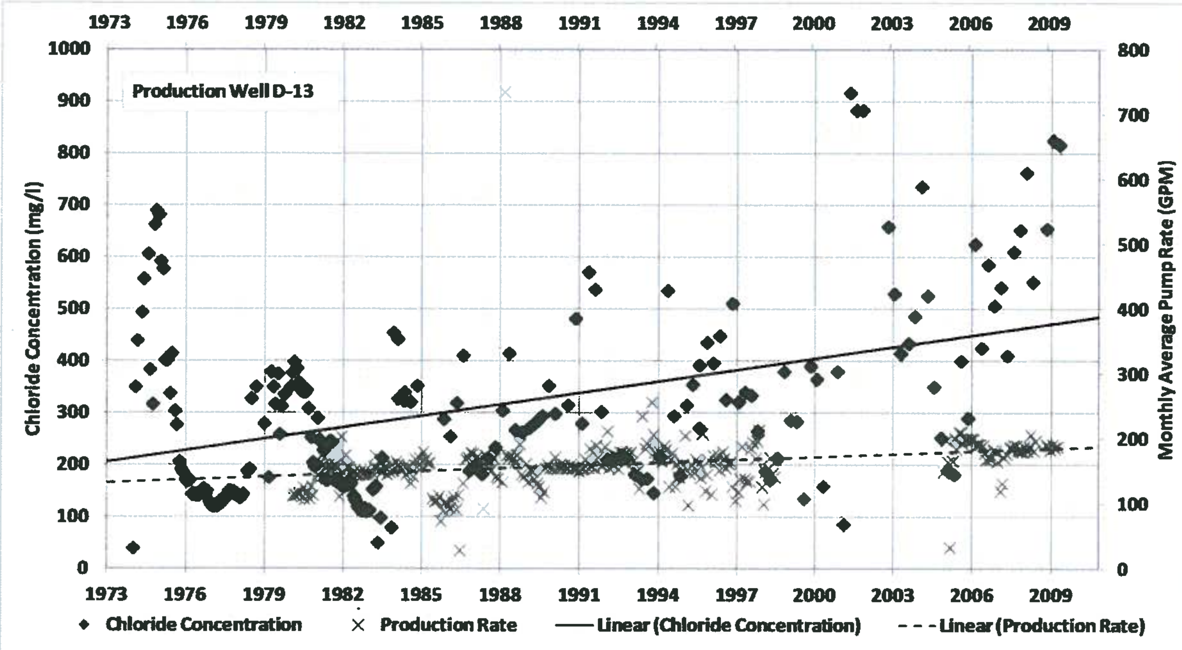


**Figure 19**: Chloride and production trends at production well D-13 in the Yigo-Tumon Basin.

example of how widely chloride concentrations can vary for wells located in the saltwater toe zone. Despite a relatively stable production rate around 200 gpm, chloride concentrations at D-13 have ranged from 39 to 917 mg/l. Chloride concentrations at D-13 are a good indicator of the saltwater toe location in this region of the Yigo-Tumon Basin.

Production well A-1 (Figure 20), located northeast of the Pago-Adelup fault in the Hagåtña Basin, is a good example of the increasing chloride concentrations at many para-basal wells that have changed chloride benchmarks from "Exceptional" (less than 30 mg/l) to "Good" (30 to 70 mg/l) in the last decade. Relatively stable chloride concentrations in the 1970s, 1980s, and 1990s are increasingly variable in the 2000s.

Production well M-17B (Figure 21) is situated in a para-basal groundwater zone on the flank of Mt. Barrigada in the Yigo-Tumon Basin where underlying volcanics are between MSL and -20 meters elevation. A cyclical chloride trend is observed at M-17B with a periodicity of 5 to 8 years, similar to the chloride trends observed in the basal groundwater zone.

Supra-basal Groundwater

Four production wells (D-22A, Y-15, Y-17, and Y-23) are located in a supra-basal groundwater zone. Given that seawater is not hydraulically connected with groundwater in the supra-basal zone, sources of chloride other than seawater, such as sea spray, airborne salt particles, industrial waste, or septic system effluent, along with chlorine-treated potable water leaking from the distribution system, may account for fluctuating chloride concentrations. Chloride concentrations in supra-basal production well Y-15 (Figure 22) exhibit an increasing trend since 1995, in which the minimum and maximum chloride concentration differs by one order of magnitude from 6 to 60 mg/l. The other supra-basal production wells have a similar range of chloride concentrations between 10 and 60 mg/l.

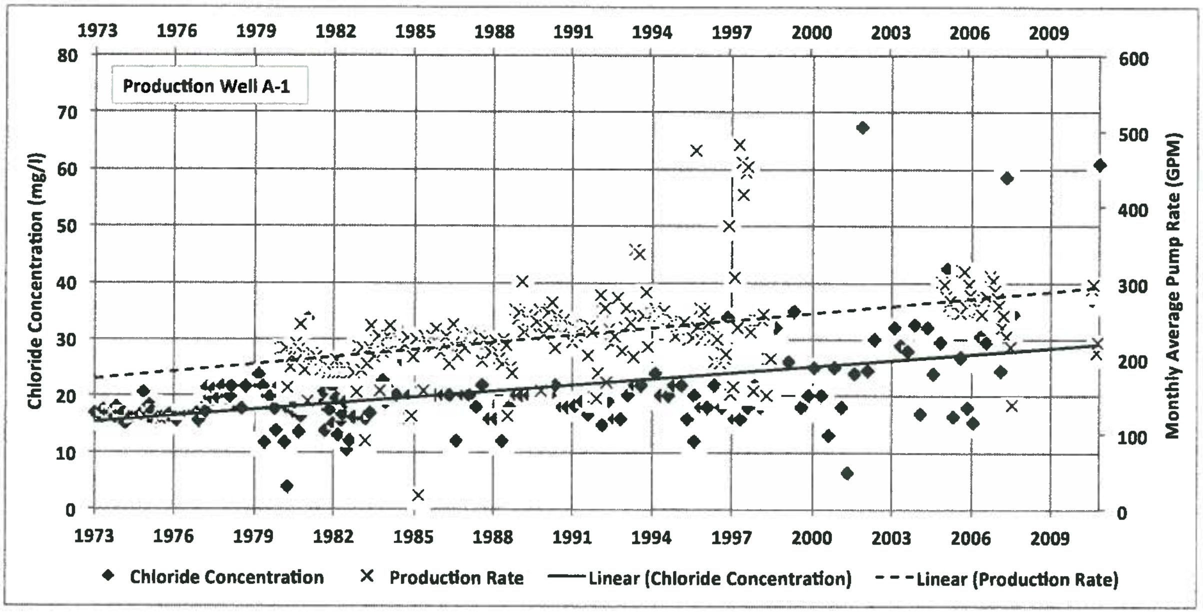


**Figure 20**: Chloride and production trends at production well A-1 in the Hagåtña Basin.

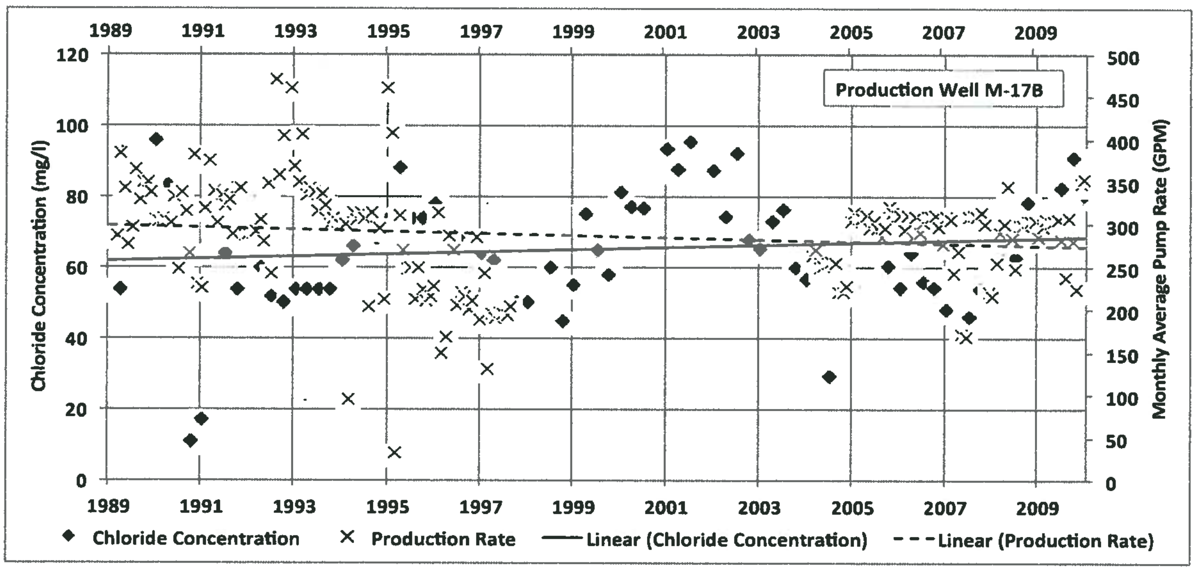


**Figure 21**: Chloride and production trends at production well M-17B in the Yigo-Tumon Basin.

### Relationship Between Chloride and Rainfall Trends

Figure 23 depicts the total annual rainfall amounts recorded at AAFB between 1973 and 2010, including the breakout of dry seasonal (January-June) and wet seasonal (July-December) rainfall. The mean annual rainfall at AAFB since 1973 is about 93.2 inches. According to Jocson et al. (2002), approximately 60% of Guam's annual rainfall is retained in the freshwater lens as "exploitable recharge", after 20% is removed via evapotranspiration and another 20% infiltrates too rapidly during heavy storm events and discharges out to sea. Most infiltration occurs when saturated soil conditions exist (Jocson et al 2002), which suggests greater "exploitable recharge" during the wet season. Therefore, approximately 56 inches per

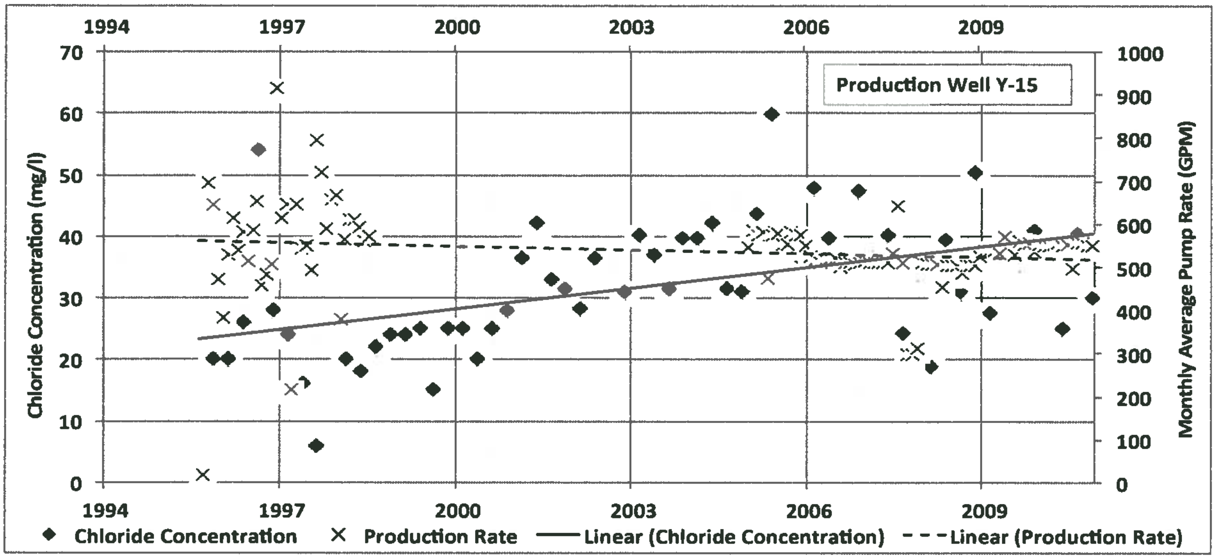


**Figure 22**: Chloride and production trends at production well Y-15 in the Andersen Basin.

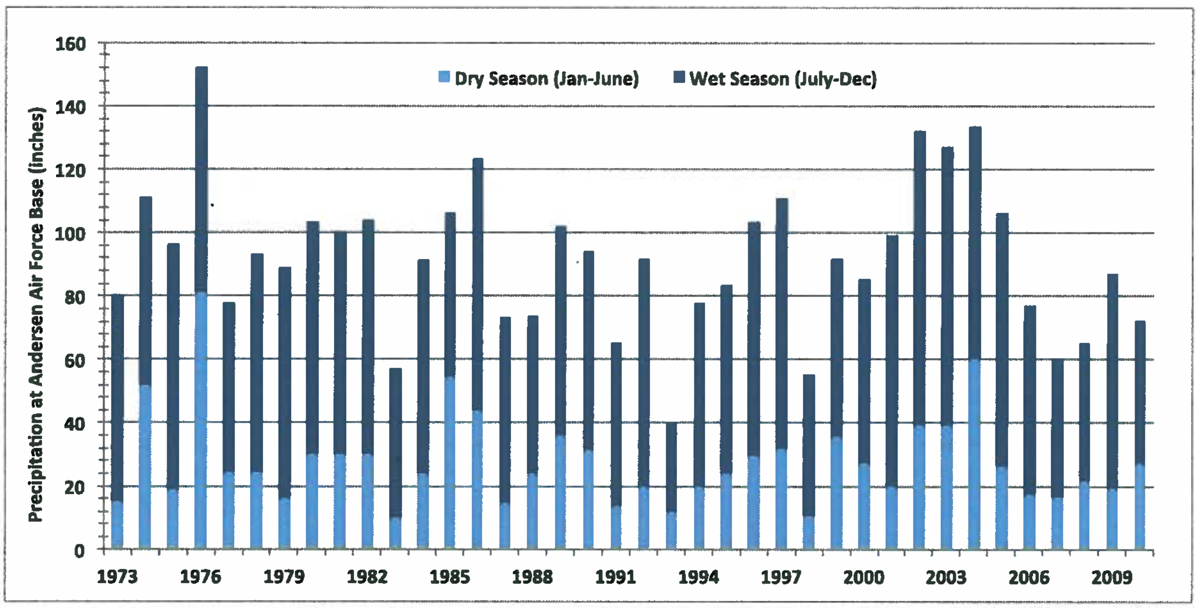


**Figure 23**: Total annual and seasonal rainfall at Andersen Air Force Base from 1973 through 2010 (NOAA, 2011).

year is considered "exploitable recharge" to the NGLA. A recent Guam water budget study by Johnson (2012) estimates that recharge to the NGLA may be lower at 51% of mean annual rainfall, or about 47.5 inches per year.

Chloride trends at selected production wells representative of the basal (A-10), para-basal (A-1), and supra-basal (Y-15) groundwater zones were compared to long-term rainfall trends from AAFB to evaluate for temporal inter-relationships. One would expect decreased groundwater chloride concentrations during periods of above-average rainfall and increased groundwater chloride concentrations during periods of below-average rainfall.

Basal Groundwater

At basal production well A-10 (Figure 24a), the chloride trend is relatively stable until 1989, at which time chloride concentrations double from 200 to 400 mg/l by 2010. There is a strong correlation between annual rainfall measurements and mean annual chloride concentrations. The sharp increase in the chloride trend at A-10 between 1989 and 1994 is likely a result of reduced above-average rainfall between 1989 and 1991 and increased below-average rainfall between 1993 and 1995. Another sharp increase in the chloride trend between 2006 and 2010 at A-10 is likely a result of five consecutive years with below-average rainfall. It appears that the cumulative effect of several consecutive years of decreased or increased rainfall is stronger than one isolated anomalous year.

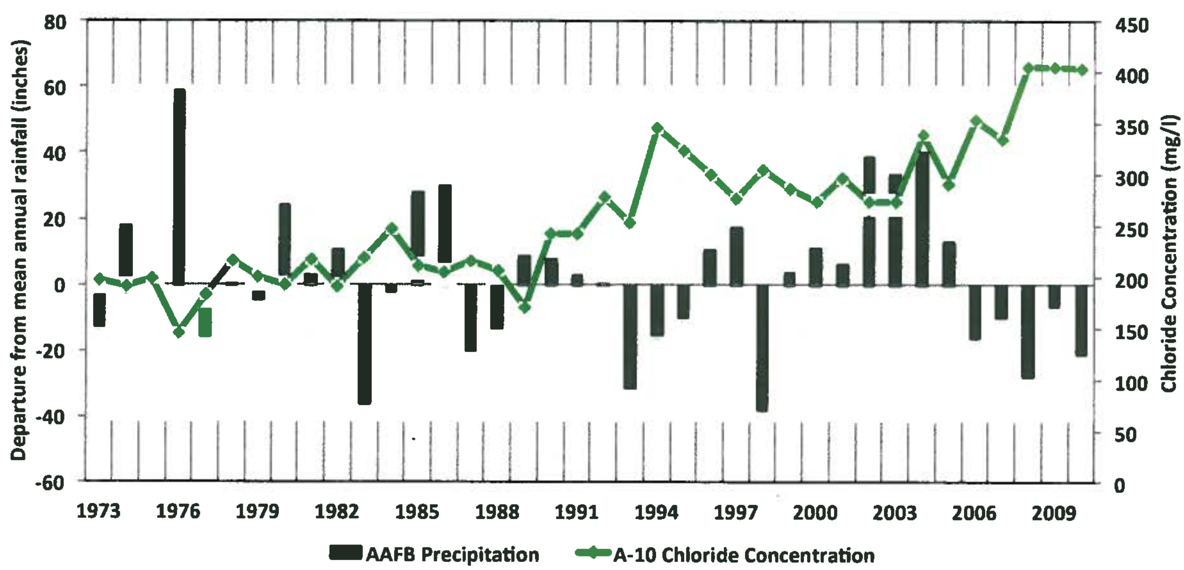


**Figure 24a**: Basal production well A-10, departure of total annual rainfall from mean annual rainfall at AAFB compared to mean annual chloride concentrations.

Para-basal Groundwater

At para-basal production well A-1 (Figure 24b), the chloride trend is relatively stable until the early 1990s, at which time the increase becomes gradual until 2006, and then a sharp increase occurs from 2006 to 2010. The sharp chloride increase between 2006 and 2010, similar to A-10, is likely a result of an extended period of reduced rainfall.

Supra-basal Groundwater

At supra-basal production well Y-15 (Figure 24c), the chloride concentrations appear to respond more gradually to rainfall than production wells A-1 and A-10. Chloride concentrations continue to increase between 1999 and 2001 despite above-average annual rainfall. Although below-average annual rainfall occurs between 2006 and 2010, the chloride trend decreases until 2007, then stabilizes, rather than decreasing continuously.

**Relationship Between Chloride and Mean Sea Level Trends**

Sea level has been recorded since 1948 at Apra Harbor on Guam's western coast (Figure 25). The sea level at Guam and throughout Micronesia is strongly affected by ENSO, with lower sea level occurring during El Niño, and higher sea level occurring during La Niña. The ENSO variations of sea level are large, and are visibly the dominant signal of natural

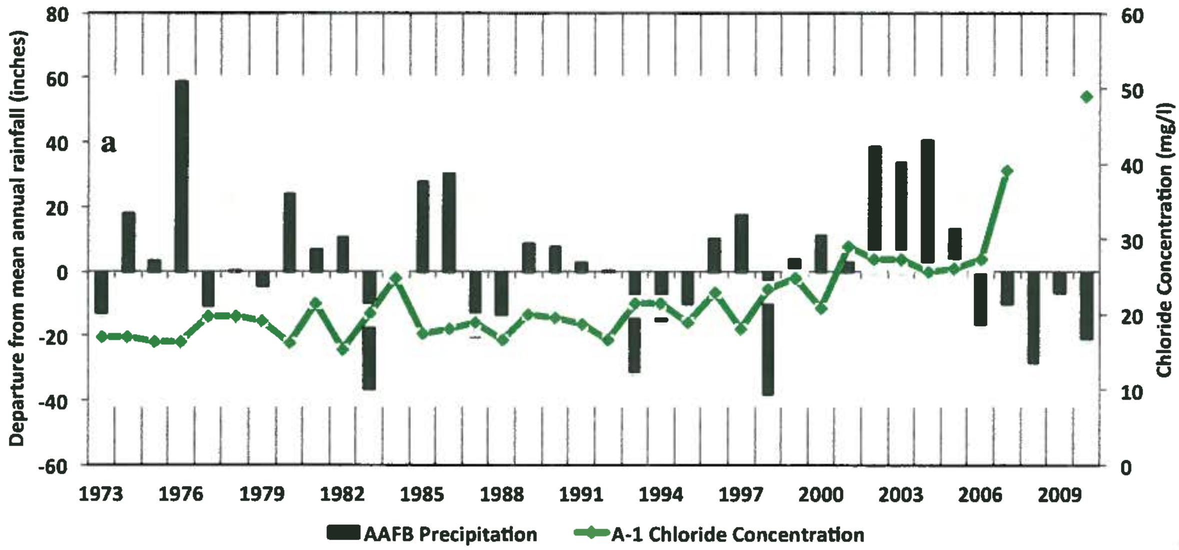


**Figure 24b**: Para-basal production well A-1.

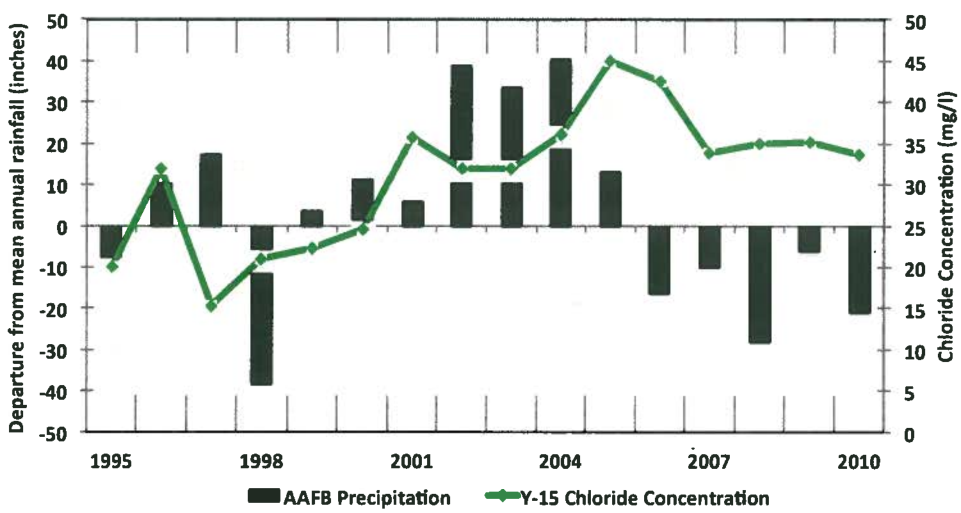


**Figure 24c**: Supra-basal production well Y-15.

variability in the time series. Another striking characteristic of the sea-level time series is best revealed by a running sum of the sea-level anomaly (Figure 25), that shows a dramatic "hockey-stick" increase of sea level for the years 1998 to present. For the period 1948 through 1997, there was no statistically significant long-term rise of sea level on Guam, or indeed, anywhere in the tropical western North Pacific. In 1997, it was still a bit of a mystery why the sea level had not shown an increase in this region. During 1998, however, the sea level rose dramatically, and stayed continually high thereafter. The step-function rise of sea level also manifests as a similar step-function increase in the strength of the Pacific trade wind system (Merrifield et al., 2012). This suggests the trade wind increase is the primary cause of recent sea-level rise on Guam and in the tropical western North Pacific. The change of decadal mean sea level was 12 cm between the 1990s and the 2000s.

Average monthly MSL measurements at Apra Harbor were compared to quarterly chloride concentrations at basal production well A-10 between 1990 and 2010 (Figure 26) to

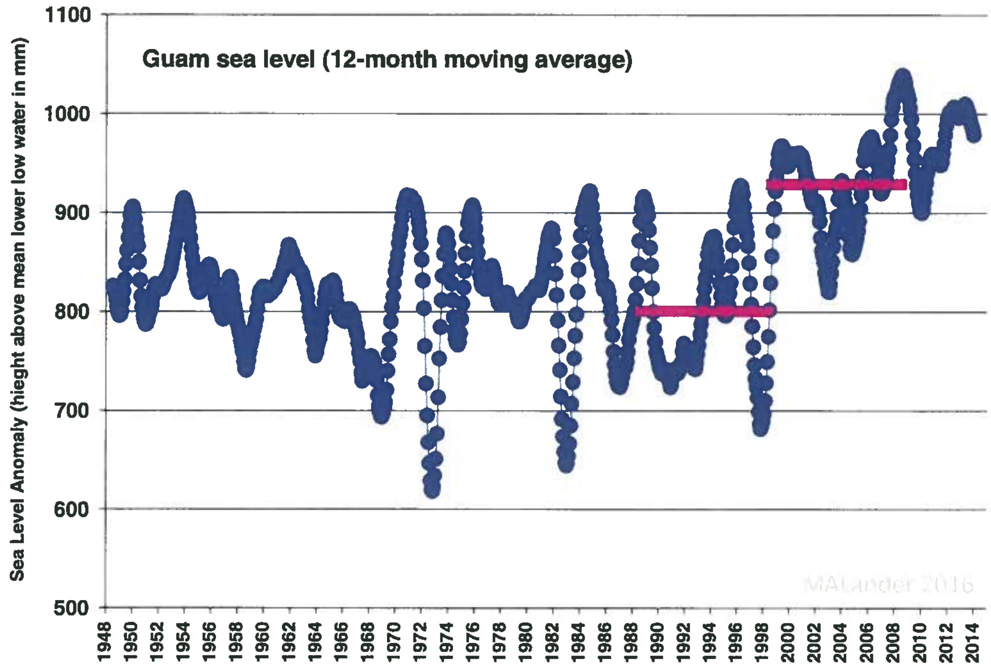


**Figure 25**: Running summation of the Apra Harbor mean sea level and Pacific trade wind anomalies recorded from 1948 to 2014.

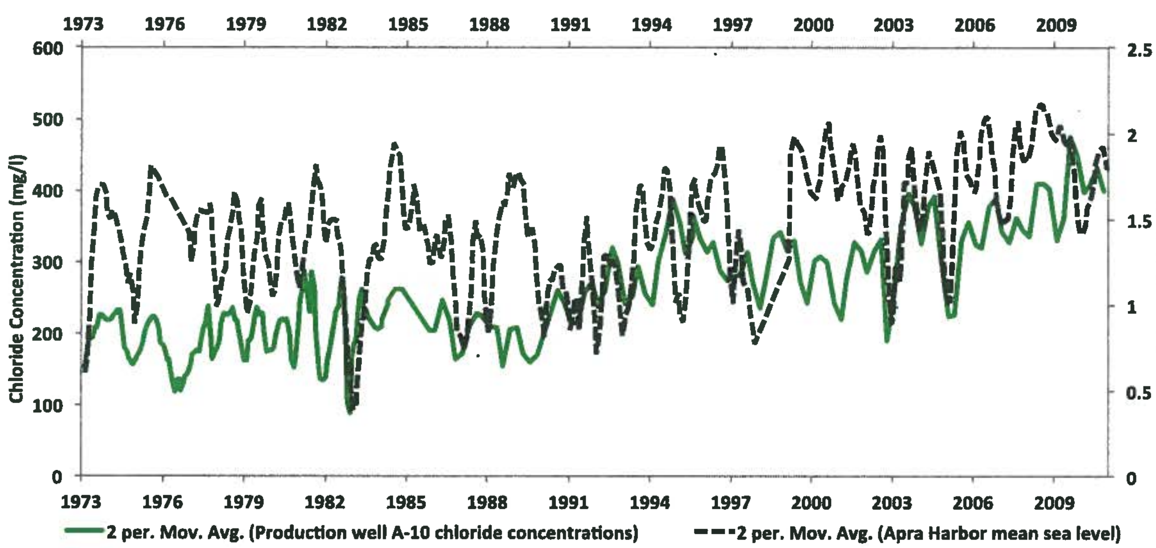


**Figure 26**: Average monthly mean sea level measurements at Apra Harbor (NOAA 2011) compared to quarterly chloride concentrations at basal production well A-10.

correlate the two datasets. Monitoring well A-10 is located centrally in the Hagåtña Basin where the volcanic basement is more than 190 meters beneath the well bottom and the freshwater lens is relatively thick. Figure 26 illustrates a strong correlation between fluctuations of MSL at Apra Harbor, indicative of sea level fluctuates across Northern Guam, and chloride concentrations at production well A-10 in the basal groundwater zone.

### Relationship Between Chloride and Southern Oscillation Index Trends

Figure 27 shows a comparison of the SOI with a five-month moving average of quarterly chloride concentrations at basal production well M-6 from 1973-2010. In the SOI, values more negative than -8 correspond to El Niño episodes, values more positive than 8 correspond to La Niña episodes, and values from 8 through -8 correspond to ENSO neutral episodes. The cyclical chloride trend at basal production well M-6, centrally located in the Yigo-Tumon Basin, appears to correspond to transitions to and from El Niño and La Niña episodes at times, but not consistently over the entire time period. The chloride trend decreases during the transition from La Niña toward El Niño episodes circa 1976-1977, 1982-1983, 1992-1993, and 2003-2007; and the chloride trend increases during the transition from El Niño toward La Niña episodes circa 1983-1984, 1995-1996, and 2009-2010. However, the chloride and SOI trends do not relate closely during the timespans of 1985-1992 and 1997-2009.

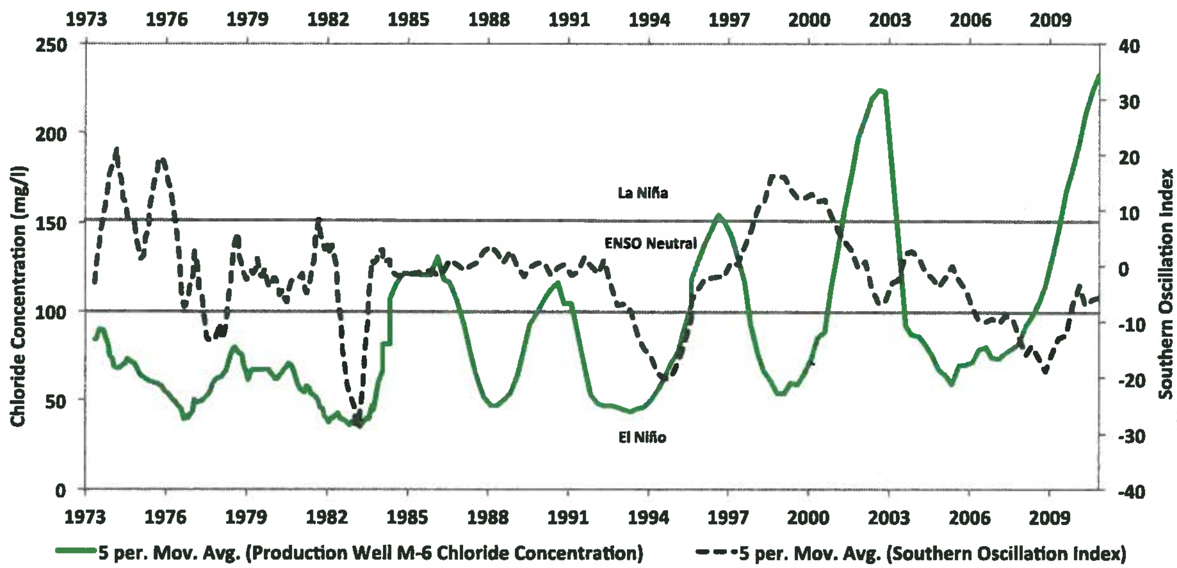


**Figure 27**: Southern Oscillation Index (Australian Bureau of Meteorology 2011) and quarterly chloride concentrations at basal production well M-6 between 1990 and 2010.

## 5.4 Analysis of Specific Conductance Data in Monitoring Wells

### Prime Layer

Using quarterly salinity profiles obtained from seven deep NGLA monitoring wells (Figure 28) from May 2005 to October 2010, Figure 29 shows the lower limit of the prime layer where groundwater quality is equivalent to 1,100 µS/cm specific conductance and 250 mg/l chloride. The prime layer contains the lowest salinity groundwater optimal for groundwater extraction and potable use. A summary table with the calculated prime layer depths is provided in Appendix D.

Hydrogeologic differences between the Hagåtña Argillaceous Limestone (EX-1 and EX-4) and Barrigada Limestone and cleaner Mariana Limestone units (EX-6, EX-7, EX-9, EX-10, and GHURA-DEDEDO) are illustrated in the prime layer trends. At EX-1 and EX-4, the prime layer fluctuated seasonally by as much as 70 meters, becoming thinner at the end of the dry season and thicker during the wet season. The shallowest prime layer elevation is consistent at about -17 to -18 meters at EX-1 and -3 to -4 meters at EX-4. These depths may

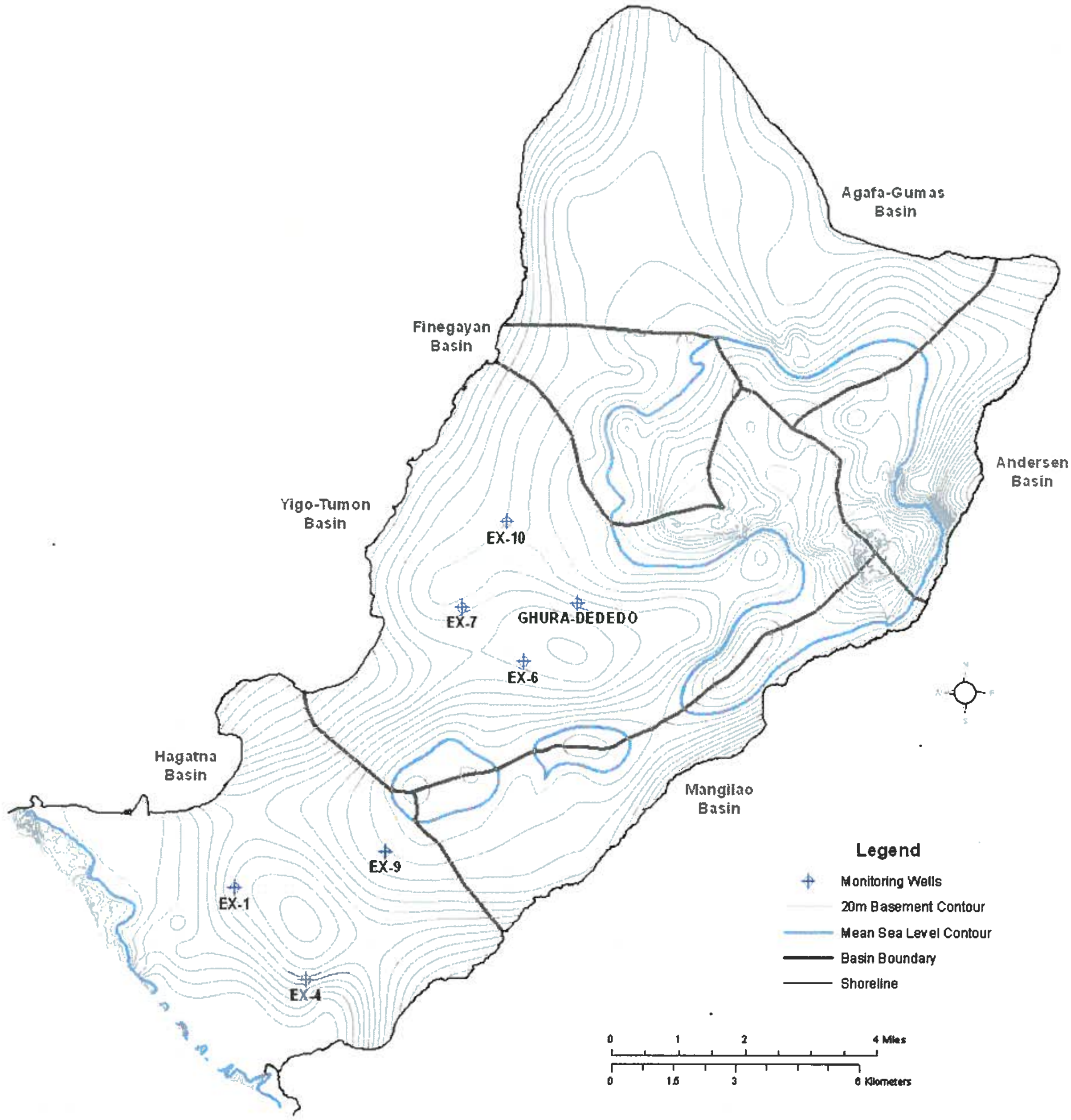


**Figure 28**: Location of NGLA monitoring wells used for salinity profiles.

represent the minimum prime layer thickness achievable in the vicinity of these monitoring wells. The deepest prime layer elevation varies among each wet season, which suggests that seasonal recharge strongly influences the prime layer thickness in the Hagåtña Argillaceous Limestone.

Monitoring well EX-9 is located in an area where the surficial geology is mapped as Hagåtña Argillaceous Limestone, but the prime layer trend behaves more like the Yigo-Tumon Basin monitoring wells. Therefore, the screened interval at monitoring well EX-9 is probably situated in Barrigada Limestone where groundwater transmissivity is higher. The lower limit of the prime layer at EX-9 decreased about 4 meters (13 feet) between 2005 and 2010, which is comparable to the prime layer decrease in the Yigo-Tumon Basin monitoring wells of about

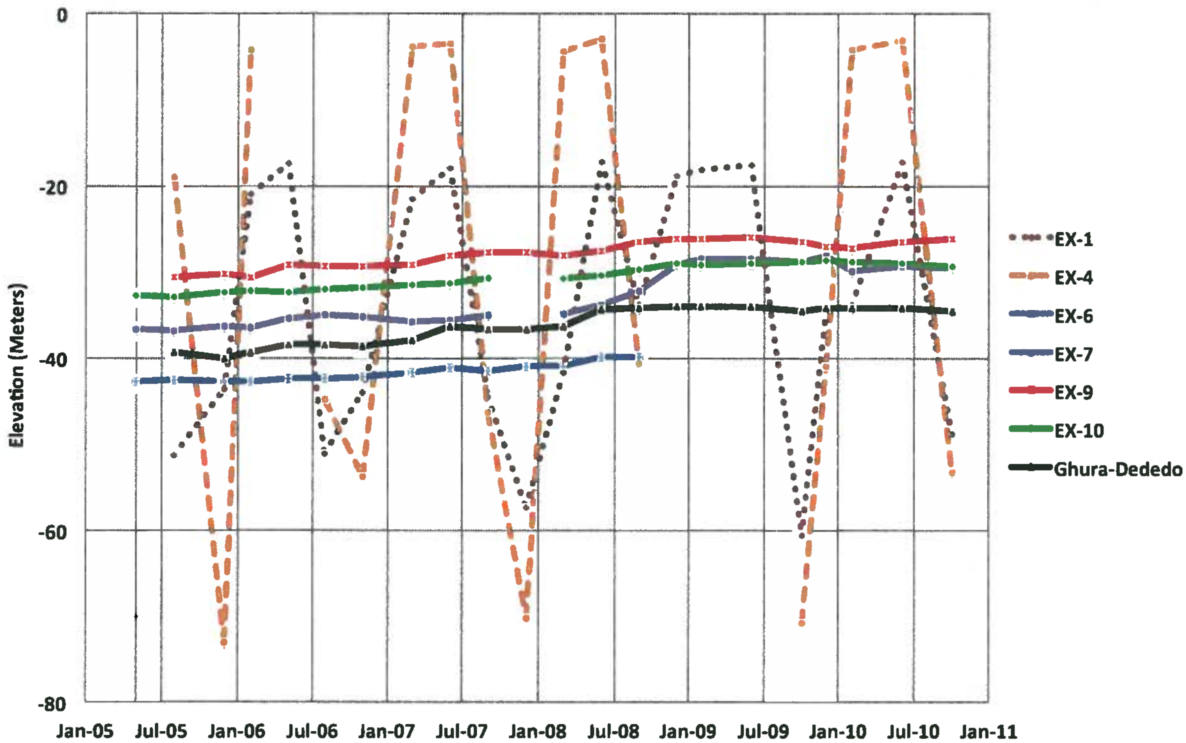


**Figure 29**: Approximate lower limit of the prime layer observed in NGLA monitoring wells. The lines for EX-1 and EX-4 are dashed to illustrate their location in the Hagåtña Argillaceous Limestone.

3 meters (10 feet; EX-6 and EX-10), 6 meters (20 feet; GHURA-DEDEDO) and 7 meters (23 feet; EX-7).

**Freshwater-Saltwater Interface**

Using quarterly salinity profiles obtained from seven deep NGLA monitoring wells (Figure 28) from May 2005 to October 2010, Figure 30 shows the freshwater-saltwater interface (50% seawater isochlor of 27,000 µS/cm specific conductance). The 50% seawater isochlor marks the lower limit of the freshwater lens. Summary tables with the calculated 50% seawater isochlor depths are provided in Appendix E.

Similar to the prime layer depths, the 50% seawater isochlor depths visually illustrate the hydrogeologic differences between the Hagåtña Argillaceous Limestone (EX-1 and EX-4) and Barrigada Limestone and cleaner Mariana Limestone (EX-6, EX-7, EX-9, EX-10, and GHURA-DEDEDO). The 50% seawater isochlor at EX-1 and EX-4 are distinctly deeper than the other monitoring wells by almost twice the vertical distance. The decreasing 50% seawater isochlor depth indicates that the freshwater lens was thinning between 2005 and 2010. The 50% seawater isochlor decreased in cleaner limestone by about 2 meters (6 feet; EX-6) to 6 meters (20 feet; EX-9 and GHURA-DEDEDO), and decreased in argillaceous limestone by about 4 meters (13 feet; EX-4) to 13 meters (43 feet; EX-1). Often the 50% seawater isochlor was below the well bottom depth of -240 feet (-73 meters) at monitoring well EX-4. Monitoring well EX-1 is constructed deep enough to consistently intersect the 50% seawater isochlor. The seasonal fluctuation of the 50% seawater isochlor at EX-1 and EX-4 follows the prime layer fluctuations, but their magnitudes are muted.

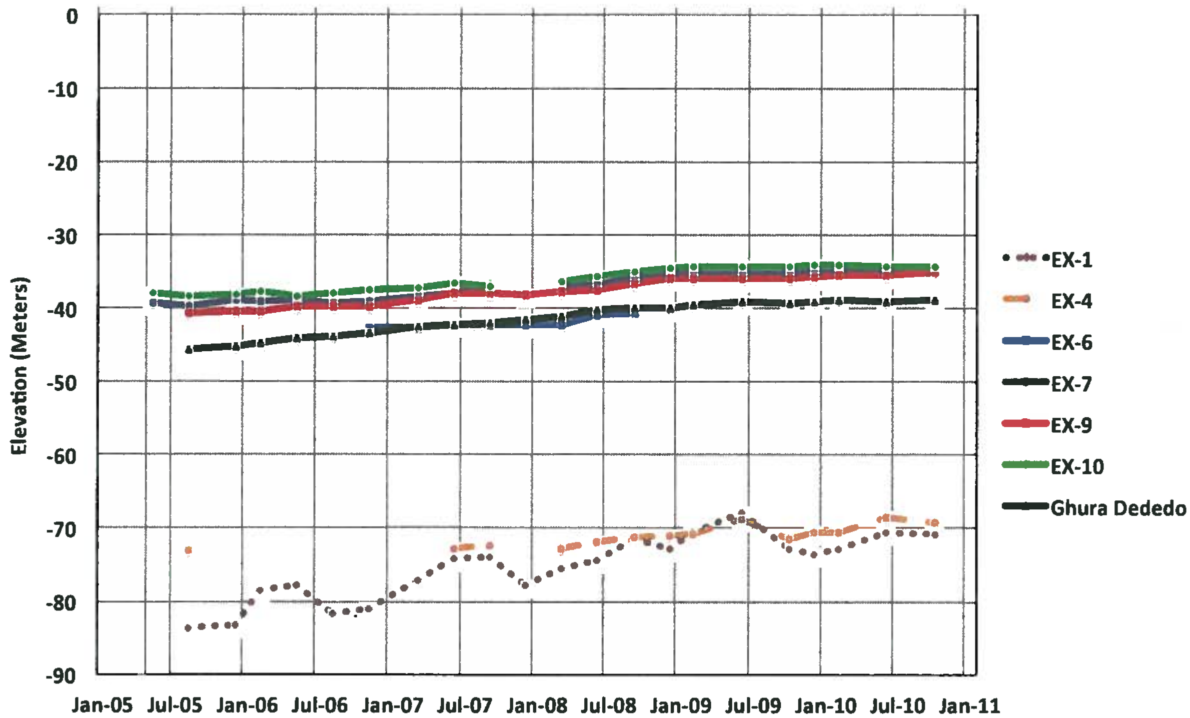


**Figure 30**: Approximate depth of the 50% seawater isochlor observed in NGLA monitoring wells. The lines for EX-1 and EX-4 are dashed to illustrate their location in the Hagåtña Argillaceous Limestone.

**Applying the Ghyben-Herzberg Principle to the NGLA**

The application of the Ghyben-Herzberg principle is commonly used to estimate the 50% seawater isochlor because it is more efficient and cost effective than obtaining salinity profiles. However, this indirect method of approximating the 50% seawater isochlor, assuming a 40:1 ratio of freshwater below MSL to hydraulic head in a well, differs from the measured 50% seawater isochlor depths obtained from salinity profiles. Hydraulic head measurements obtained during the quarterly salinity profiles were used to calculate the 50% seawater isochlor applying the Ghyben-Herzberg principle. Comparisons of the 50% seawater isochlor depths obtained from measured salinity profile data and inferred using hydraulic head measurements are provided in Appendix E.

It is well understood that the Ghyben-Herzberg principle is applicable to steady-state conditions and does not account for dynamic flow and mixing that occurs in the transition zone. Given the technical rigor used by USGS to generate the salinity profiles, the 50% seawater isochlor depths obtained from the direct specific conductance measurements serve as baseline measurements. The 50% seawater isochlor depths, calculated by applying the 40:1 Ghyben-Herzberg ratio to measured hydraulic head measurements, differ from the salinity profiles by as much as 97.93 feet or 29.85 meters (EX-1 in October 2010). The ratio of freshwater below MSL to freshwater above MSL ranges from approximately 28:1 to 46:1 among the various monitoring wells, with a mean ratio of 37:1. In most instances, the 40:1 Ghyben-Herzberg ratio overestimates the depth of the 50% seawater isochlor.

The mean ratio of 37:1 was applied to the minimum, maximum, and mean hydraulic head measurements recorded at 12 monitoring wells throughout the NGLA between 1975 and 2010 to determine the upper limit, lower limit, and mean of the 50% seawater isochlor depths at those locations, respectively (Table 18). These minimum and maximum 50% seawater isochlor depths indicate that the freshwater-saltwater interface fluctuated between about -15 and -120 meters (-50 and -394 feet) elevation depending on the monitoring well's location within the NGLA. The mean freshwater-saltwater interface depth for all monitoring wells ranges between about -30 and -80 meters (-98 and -264 feet) elevation.

**Table 18**: Summary of hydraulic head measurements and calculated 50% seawater isochlor depths using a 37:1 ratio based on the Ghyben-Herzberg principle

| Monitoring Well | Min | 50% Isochlor (37:1 ratio) | | Max | 50% Isochlor (37:1 ratio) | | Mean | 50% Isochlor (37:1 ratio) | |
|---|---|---|---|---|---|---|---|---|---|
| | feet | feet | meters | feet | feet | meters | feet | feet | meters |
| A-16 | 2.86 | -105.82 | -32.25 | 7.10 | -262.70 | -80.07 | 3.74 | -138.38 | -42.18 |
| A-20 | 30.69 | NA | NA | 62.35 | NA | NA | 41.51 | NA | NA |
| BPM-1 | 1.93 | -71.41 | -21.77 | 5.80 | -214.60 | -65.41 | 2.92 | -108.04 | -32.93 |
| EX-1 | 5.25 | -194.25 | -59.21 | 10.64 | -393.68 | -119.99 | 7.14 | -264.18 | -80.52 |
| EX-4 | 4.78 | -176.86 | -53.91 | 8.08 | -298.96 | -91.12 | 5.88 | -217.56 | -66.31 |
| EX-6 | 3.40 | -125.80 | -38.34 | 4.40 | -162.80 | -49.62 | 3.81 | -140.97 | -42.97 |
| EX-7 | 2.45 | -90.65 | -27.63 | 5.56 | -205.72 | -62.70 | 3.34 | -123.58 | -37.67 |
| EX-8 | 1.86 | -68.82 | -20.98 | 4.49 | -166.13 | -50.64 | 2.64 | -97.68 | -29.77 |
| EX-9 | 2.33 | -86.21 | -26.28 | 4.34 | -160.58 | -48.94 | 3.30 | -122.10 | -37.22 |
| EX-10 | 1.93 | -71.41 | -21.77 | 4.79 | -177.23 | -54.02 | 2.94 | -108.78 | -33.16 |
| Ghura-Dededo | 1.35 | -49.95 | -15.22 | 5.29 | -195.73 | -59.66 | 3.52 | -130.24 | -39.70 |
| M-10A | 3.39 | -125.43 | -38.23 | 5.19 | -192.03 | -58.53 | 3.00 | -111.00 | -33.83 |
| M-11 | 2.49 | -92.13 | -28.08 | 8.25 | -305.25 | -93.04 | 3.55 | -131.35 | -40.04 |

Table 19 compares the 50% seawater isochlor depths obtained from the 2005 to 2010 salinity profiles with those calculated from the 37:1 ratio applied to historical hydraulic head measurements. This comparison suggests that the 50% seawater isochlor historically has been shallower and deeper than the depths observed during the salinity profiles obtained from 2005 through 2010.

**Table 19**: Comparison of calculated 50% seawater isochlor depths at NGLA monitoring wells.

| Calculated Depths of 50% Isochlor in the NGLA | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Monitoring Well | 2005-2010 Salinity Profiles | | | | 37:1 Ratio Applied to Water Levels | | | |
| | Minimum | | Maximum | | Minimum | | Maximum | |
| | feet | meters | feet | meters | feet | meters | feet | meters |
| EX-1 | -222.46 | -67.81 | -274.4 | -78.21 | -194.25 | -59.21 | -393.68 | -119.99 |
| EX-4 | -224.90 | -68.55 | > -240 | > -73.15 | -176.86 | -53.91 | -298.96 | -91.12 |
| EX-6 | -133.44 | -40.67 | > -140 | > -42.67 | NA | NA | NA | NA |
| EX-7 | -114.33 | -34.85 | -130.64 | -39.82 | -90.65 | -27.63 | -205.72 | -62.70 |
| EX-9 | -115.06 | -35.07 | -133.56 | -40.71 | -86.21 | -26.28 | -160.58 | -48.94 |
| EX-10 | -112.08 | -34.16 | -125.94 | -38.39 | -71.41 | -21.77 | -177.23 | -54.02 |
| Ghura-Dededo | -127.45 | -38.85 | -149.61 | -45.60 | -49.95 | -15.22 | -195.73 | -59.66 |

### 5.5 2005-2010 Fluctuations in Lens Thickness

Cross-sectional diagrams illustrate historical fluctuations of the freshwater lens and freshwater-saltwater interface (50% seawater isochlor) between 2005 and 2010, based on salinity profiles using specific conductance data collected at three monitoring wells located in high-producing parts of the aquifer (Figure 31). The first cross-section (A-A′, Figure 32) lies in one of the most heavily developed portions of the basal zone in the Yigo-Tumon Basin. The

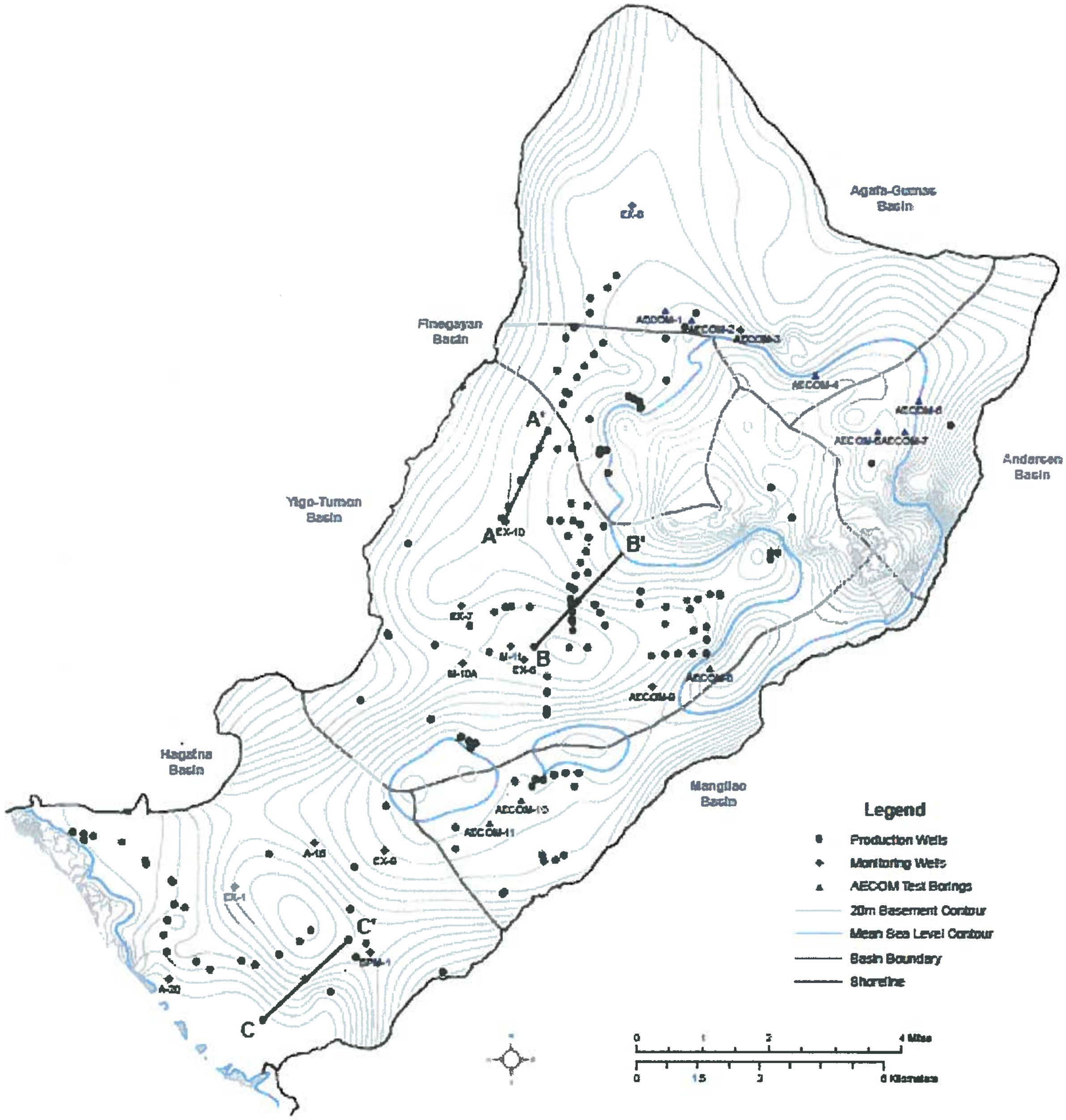


**Figure 31**: Cross-section location map. A-A′ extends NNW from well EX-10 and straddles a line of production wells in the densely developed basal zone in the Yigo-Tumon Basin. B-B′ straddles well EX-4 and extends NW from the flank of the Pago-Adelup footwall across the para-basal zone to the basal zone in the Hagåtña Basin. C-C′ straddles GHURA-DEDEDO well and extends SW from the SW flank of the Mataguac Rise across the para-basal zone to the basal zone in the Yigo Trough.

other two cross-sections extend from the para-basal zone into the basal zone in the Hagåtña Basin (B-B′, Figure 33) and across the Yigo Trough (C-C′, Figure 34), respectively.

**Basal Zone: EX-10, Yigo-Tumon Basin**

In Figure 32, the cross-section depicts a basal groundwater zone parallel to the western coastline in the Yigo-Tumon Basin. Monitoring well EX-10 and production wells F-19, F-6

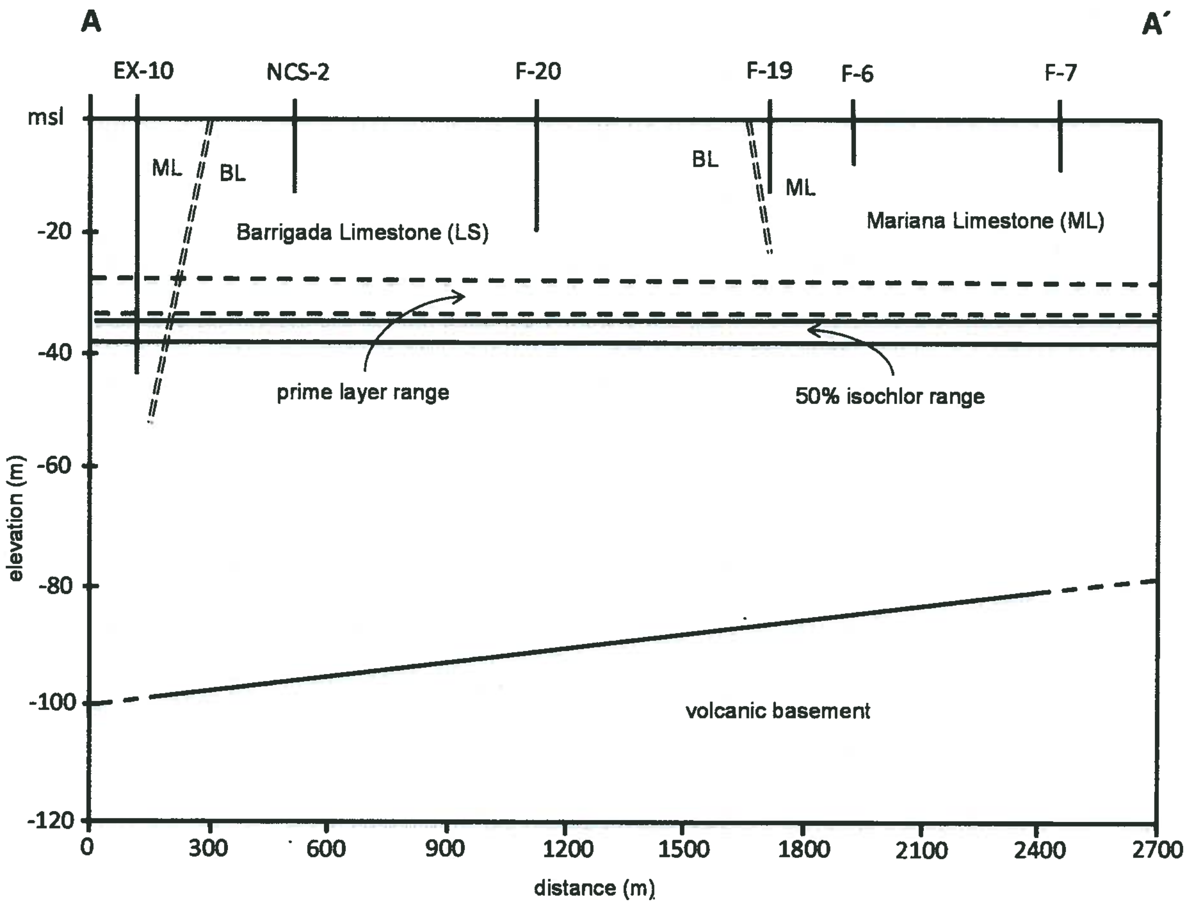


**Figure 32**: Cross-section A-A′ of Yigo-Tumon Basin near monitoring well EX-10.

and F-7 are situated in Mariana Limestone, while production wells NCS-2 and F-20 are situated in Barrigada Limestone. Based on well bottom depths, the production wells in this area lie completely within the prime layer. At monitoring well EX-10 between 2005 and 2010, the lower limit of the prime layer ranged from about -28 to -33 meters elevation and the 50% seawater isochlor ranged from about -34 to -38 meters elevation. Salinity profiles show that the prime layer maintained an equidistant position relative to the 50% seawater isochlor as it fluctuated.

**Para-Basal to Basal Zone: GHURA DEDEDO, Yigo-Tumon Basin**

In Figure 33, the cross-section depicts basal and para-basal groundwater zones in the central region of the Yigo-Tumon Basin. Monitoring well GHURA-DEDEDO and surrounding production wells are situated in Barrigada Limestone. Based on inferred depths, the production wells in this area lie completely within the freshwater lens. At GHURA-DEDEDO between 2005 and 2010, the lower limit of the prime layer ranged from about -34 to -40 meters elevation and the 50% seawater isochlor depth ranged from -39 to -46 meters elevation. Similar to the area surrounding EX-10, the freshwater lens maintained an equidistant position relative to the 50% seawater isochlor.

**Para-Basal to Basal Zone: EX-4, Hagåtña Basin**

In Figure 34, the cross-section depicts the prime layer and 50% seawater isochlor within basal and para-basal groundwater zones in the southwest region of the Hagåtña Basin.

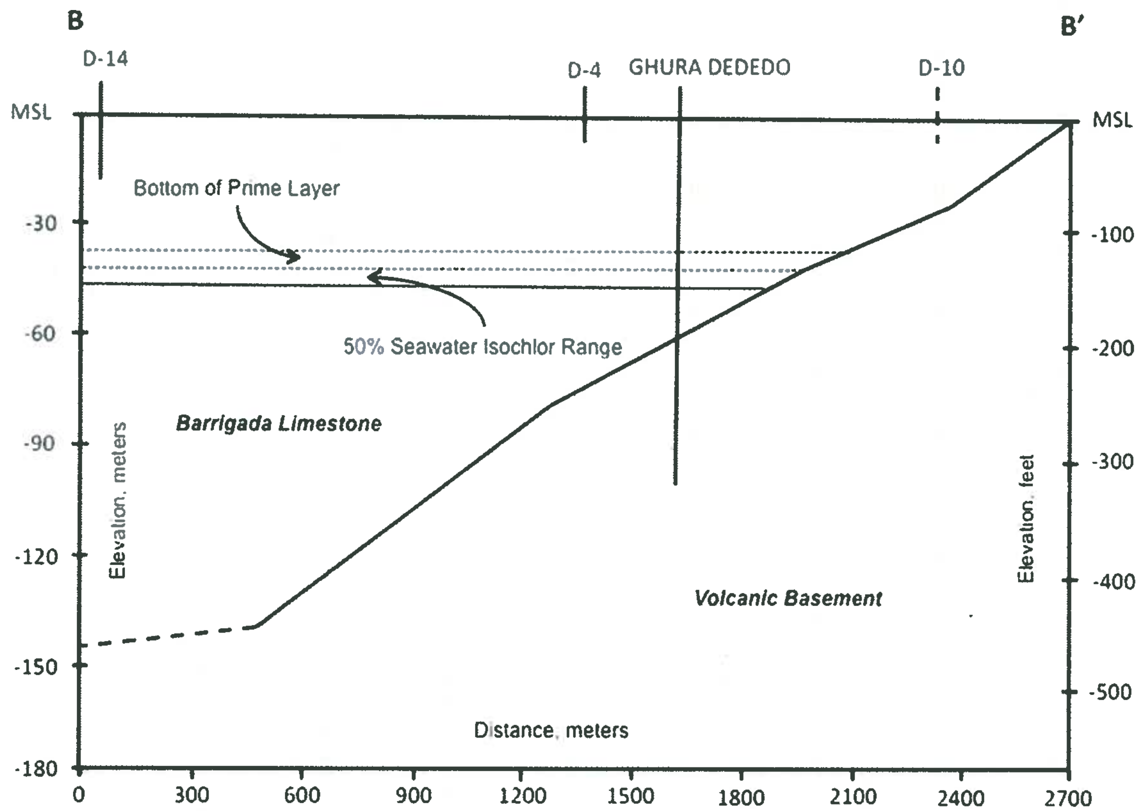


**Figure 33**: Cross-section B-B′ of Yigo-Tumon Basin near monitoring well GHURA-DEDEDO.

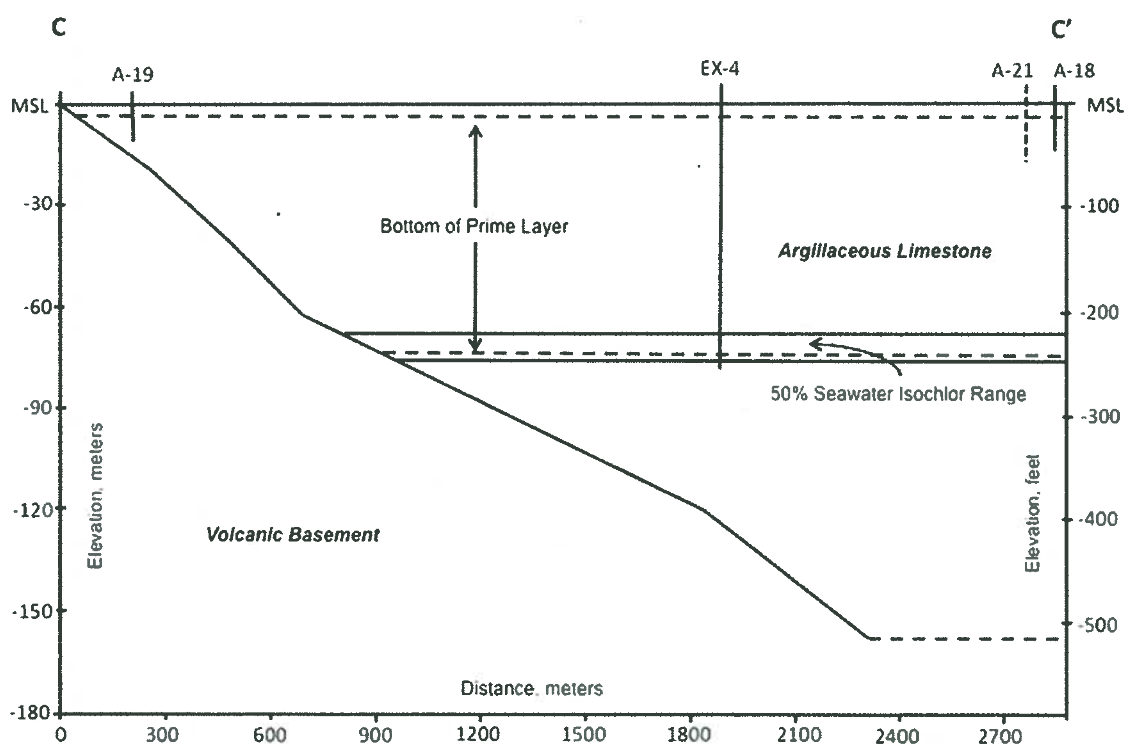


**Figure 34**: Cross-section C-C′ of Hagåtña Basin near monitoring well EX-4.

Monitoring well EX-4 and surrounding production wells are situated in the Hagåtña Argillaceous member of the Mariana Limestone. At EX-4 between 2005 and 2010, the lower limit of the prime layer ranged from about -3 meters to the well bottom at -73 meters elevation. The 50% seawater isochlor depth ranged between about -68 meters to the well bottom at -73 meters elevation, with an overall decreasing elevation. Assuming that salinity conditions at monitoring well EX-4 are indicative of actual aquifer conditions in the local area, groundwater salinity increases in the local production wells during the dry season when the prime layer is thinnest. Conversely, groundwater salinity decreases in the local production wells during the wet season when the prime layer is thickest.

# 6 CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Conceptual Understanding of Salinity for the NGLA

### General Conclusions

Salinity conditions within the NGLA are dynamic, and the snapshot of the aquifer obtained from the production well chloride samples and monitoring well specific conductance measurements provide limited but important insights into those dynamics. It is important to keep in mind that the NGLA consists of a heterogeneous triple porosity system (matrix, fracture, and conduit porosity), and groundwater conditions at one well may not apply even a few meters away at another well. As shown in Table 20, a hydraulic connection to brackish water or seawater is considered a probable cause for all production wells, but is especially applicable to those production wells with greater than 150 mg/l chloride. Another probable cause applicable to all production wells is non-seawater sources, as indicated by increasing chloride concentrations at production wells in the supra-basal groundwater zone.

Other sources of chloride potentially affecting the NGLA include sea spray, salt aerosols forming condensation nuclei in rainfall and carried by winds, salinization of soils from irrigation and agricultural practices, and leakage from septic systems, industrial waste, and infrastructure containing chlorine-treated potable water.

Chloride concentrations exhibited significant increasing trends at 107 of 153 (70%) freshwater production wells between 1973 and 2010. The 2000-2010 decade experienced higher pumping rates and higher chloride concentrations than any of the previous decades at a majority of the production wells, throughout all six basins. The chloride trends were relatively stable during the 1970s and 1980s, adhering closely to their established patterns, but increased variability occurred during the 1990s and 2000s.

Cyclical chloride trends, with varying periodicity, were observed at production wells in basal and para-basal groundwater zones. At many of those production wells, the magnitude of the chloride cycle also increases over time, which coincides with the increased variability exhibited in the last two decades. The addition of more production wells combined with increasing pumping rates at many production wells in the past few decades may be causing increased mixing of variable density and variable salinity groundwater within the aquifer. Hydrologic factors may also be contributing to the increased variability, such as periods of below-average rainfall and increasing MSL.

In the private freshwater production wells, chloride concentrations have been relatively stable, which is probably a combination of low production and sample frequency. Also, the private freshwater wells, even though some are clustered, tend to be isolated without any surrounding

**Table 20**: List of production wells with elevated chloride concentrations (greater than 150 mg/l) and probable causes of elevated salinity conditions.

| NGLA Production Well | 2000-10 Mean Chloride Concentration (mg/l) | PROBABLE CAUSES OF SALINITY CONDITIONS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Termination depth exceeds NGLS guidelines | Excessive pumping (exceeds NGLS guidelines and/or permit rate) | Seasonal thinning of freshwater lens (Hagatna Argillaceous LS) | Upgradient well(s) reducing recharge | Proximity to saltwater toe | Proximity to coastline | Hydraulic connection to brackish water or seawater via fractures or conduits | Other / Non-seawater sources |
| A-9 | 214.7 | x | | x | | | | x | x |
| A-10 | 341.7 | | x | x | | | | x | x |
| A-13 | 424.5 | x | | x | | | | x | x |
| A-14 | 309.6 | x | | x | | | | x | x |
| A-15 | 162.6 | x | x | | | | | x | x |
| A-17 | 437 | | x | x | | x | | x | x |
| A-18 | 362 | x | x | x | | | | x | x |
| A-19 | 400.9 | | x | x | | | | x | x |
| A-21 | 400.4 | x | x | x | | | | x | x |
| A-28 | 175 | | x | x | | | | x | x |
| D-8 | 283.7 | | | | | | | x | x |
| D-9 | 180.4 | | | | | x | | x | x |
| D-13 | 518.1 | x | | | | | | x | x |
| D-17 | 171.2 | | | | | | | x | x |
| D-26 | 256.8 | x | x | | x | | | x | x |
| F-4 | 192.7 | | | | | | | x | x |
| F-6 | 359.9 | | | | x | | | x | x |
| F-10 | 291.9 | x | | | | | | x | x |
| F-11 | 174.4 | x | | | | | | x | x |
| F-13 | 260.6 | x | | | | x | | x | x |
| F-19 | 251.9 | x | | | x | | | x | x |
| F-20 | 278.8 | x | | | | | | x | x |
| H-1 | 173.6 | x | x | | | | n | x | x |
| HRP-1 | 164.6 | | | | | | n | x | x |
| HRP-2 | 198.8 | | | | | | n | x | x |
| M-1 | 162.8 | | | | x | | | x | x |
| M-9 | 171.6 | x | | | x | x | | x | x |
| MGC-1 | 202.1 | | | | | | n | x | x |
| MGC-2 | 213.2 | | | | | | n | x | x |
| NCS-A | 285.1 | | | | x | | | x | x |
| NCS-2/2A | 193.2 | x | x | | | | | x | x |
| NCS-3/3A | 182.2 | x | | | | x | | x | x |
| NCS-5 | 164.9 | | | | | | | x | x |
| NCS-10 | 177.8 | | | | | | | x | x |

production wells to affect local groundwater quality via higher extraction rates and saltwater intrusion. The private freshwater production wells extract approximately 25-30 million gallons per year from the NGLA, which is very minor compared to the roughly 43 million gallons per day extracted by GWA and NAVFACMAR production wells.

Production well bottom depths and pumping rates were compared to well design guidelines established in the NGLS to evaluate if improper well construction and/or management were related to elevated or increasing chloride concentrations. Chloride concentrations exceeded 150 mg/l at 17 of the 78 (21.8%) production wells that exceed NGLS bottom depth guidelines and 10 of the 35 (28.6%) production wells that exceed NGLS pumping rate guidelines (Table 19). Excessive depth or pumping is likely contributing to elevated chlorides at 27 of the 33 (81.8%) production wells exceeding 150 mg/l. There are many data gaps regarding well construction information, particularly well screen interval.

The specific conductance value of 1,100 µS/cm was established as the NGLA-specific equivalent to 250 mg/l chloride through correlation of chloride and conductivity measurements recorded from thousands of NGLA groundwater samples. The 1,100 µS/cm specific conductance value agrees with the specific conductance to salinity conversions provided by Wagner et al. (2006). Groundwater containing greater than 250 mg/l chloride exceeds the U.S. EPA drinking water standard, so it was important to establish a conductivity equivalent to chloride that could identify the lower limit of the prime layer in the salinity profiles. The salinity profiles may contain as much as 8 to 15% error when specific conductance is less than

1,000 μS/cm (USGS 2011); therefore, the prime layer depths should be considered approximate to that level of accuracy. Greater accuracy (less than 5% error) exists with the calculated 50% seawater isochlor depths.

The relative amount of clay contained in the limestone directly affects its permeability, where the Hagåtña Argillaceous limestone has lower permeability than the Barrigada Limestone and cleaner Mariana Limestone units. The freshwater lens behaves differently between the Hagåtña Argillaceous Limestone and the other NGLA limestones. The prime layer exhibited a seasonal fluctuation in the argillaceous limestone, becoming thinner during the dry season (January to June) and thicker during the wet season (July to December) between 2005 and 2010; whereas the prime layer progressively thinned in the cleaner limestone units, showing little seasonal fluctuation. Many of the most elevated chloride production wells in the NGLA are situated in the Hagåtña Argillaceous Limestone where the prime layer can fluctuate as much as 70 meters. When the prime layer is shallower than the bottom depths of these elevated chloride production wells, the wells are extracting higher salinity groundwater, particularly during the dry season. During the wet season, the lower limit of the prime layer becomes deeper, approaching the 50% seawater isochlor, and the production wells are extracting lower salinity groundwater.

Calculated 50% seawater isochlor depths using hydraulic head measurements recorded during the salinity profiles revealed that the ratio of freshwater below sea level to freshwater above sea level can range from 29:1 to 46:1, with a mean ratio of 37:1. Werner and Simmons (2009) report that the density ratio varies between 33 and 50 for typical densities of fresh groundwater and seawater. The proposed 37:1 ratio is considered a mean estimate when approximating the 50% seawater isochlor from hydraulic head measurements. Applying the 37:1 ratio to historical hydraulic head measurements at 12 monitoring wells throughout the NGLA, the 50% seawater isochlor historically has been both shallower and deeper than the depths observed in the 2005 to 2010 salinity profiles. The minimum and maximum 50% seawater isochlor depths at each monitoring well are considered the minimum and maximum extent of the saltwater toe in those areas. Those production wells situated within this saltwater toe range are not strictly considered basal or para-basal wells, but may oscillate between these two groundwater zones depending on the current location of the saltwater toe.

The distance between the lower limit of the prime layer and 50% seawater isochlor is generally equidistant, but small, at the cleaner limestone monitoring wells EX-6, EX-7, EX-8, EX-9, EX-10 and GHURA-DEDEDO. Less than 1 meter separated the prime layer and 50% seawater isochlor at EX-6, and the maximum distance of 10 meters occurred at EX-10. At EX-1 and EX-4 in the argillaceous limestone, the distance between the prime layer and 50% seawater isochlor is smaller during the wet season when the prime layer is thickest. During the dry season, the lower limit of the prime layer is shallower and the salinity gradually increases over a longer distance until reaching the 50% seawater isochlor.

**Agafa Gumas Basin**

In the Agafa Gumas Basin, groundwater exhibits relatively low chloride concentrations and supports relatively high production rates in seven production wells. However, chloride concentrations have shown increasing trends in the past decade to bring overall groundwater quality in the basin to "Good" (30 to 70 mg/l chloride). Excessive depth and excessive/increasing pump rates may be contributing to the chloride increase, especially if the freshwater lens thinned between 2005 and 2010. Recent hydraulic head measurements at monitoring wells AECOM-3 and EX-8 differed by about 27 feet, which suggests a highly variable freshwater lens thickness across the para-basal and basal groundwater zones in this basin. The 50% seawater isochlor at monitoring well EX-8 historically fluctuated between about -20 and -50 meters elevation. The collection of salinity profiles at monitoring well EX-8 is recommended to better evaluate groundwater salinity in the Agafa Gumas Basin.

**Andersen Basin**

The groundwater salinity of the Andersen Basin is not well understood with only two production wells. Given the large monitoring well network present at AAFB, a review of the production well data with chloride and other groundwater quality data collected from AAFB is recommended. The Andersen Basin historically had more production wells, but they were abandoned due to elevated chloride concentrations. Low chloride at basal production well BPM-1 is attributed to low production rates and a modest well depth. Supra-basal production well Y-15 has sustained high production rates since 1995, but chloride concentrations show increasing trends. Non-seawater salt sources are likely contributing to increasing chloride trends at Y-15, but the well could also be hydraulically connected to higher salinity groundwater through fractures in the basement volcanics.

**Finegayan Basin**

In the Finegayan Basin, 67% of the production wells exhibit significantly increasing chloride trends. Most production wells in this basin either exceed the NGLS well bottom guidelines or their construction depth is unknown. Increasing chloride concentrations, particularly since 2000, are likely the result of excessive production well depths and a thinning of the freshwater lens between 2005 and 2010. Supra-basal production well D-22A has exhibited a wide range of chloride concentrations, from 14 to 219 mg/l, which suggests that the supra-basal groundwater zone is influenced by non-seawater salt sources or the production well intersects higher salinity groundwater through fractures (similar to Y-15). Recently converted production well NCS-A is the only monitoring well in this basin.

**Hagåtña Basin**

In the Hagåtña Basin, groundwater salinity varies among three regions: the southern para-basal region with low chloride groundwater; the southeast and central basal region with high chloride groundwater, and the remaining northern region with mid-range chloride groundwater. The para-basal production wells in the southern region have been producing "Exceptional" to "Good" quality groundwater for over four decades, despite some that are set much deeper than recommended NGLS bottom depths. The southeast and central basal region has been producing elevated chlorides since the 1970s, and yet pumping rates continue to increase at many production wells. The basal and para-basal production wells in the northern region are generally producing "Standard" quality groundwater. Despite regional salinity conditions in the Hagåtña Basin, 77% of the production wells exhibit significant increasing chloride trends. Increasing chloride trends are attributed to a combination of excessive pumping and well bottom depths, a seasonal fluctuation of the prime layer in the southeast and central region, and an overall thinning of the freshwater lens between 2005 and 2010.

**Mangilao Basin**

In the Mangilao Basin, the catchment area of the para-basal groundwater zone, where eight GWA production wells are located, is relatively small. The most up-gradient production wells appear to contain the lowest chloride concentrations. Down-gradient GWA production wells M-1 and M-9 and private freshwater production wells HRP-1, HRP-2, HGC-1, HGC-2, HGC-3 (now abandoned) and HGC-4 contain "Marginal" quality groundwater. The production wells in the basal groundwater zone are in close proximity to the coastline and are susceptible to seawater intrusion. Significantly increasing chloride trends occur at 50% of the Mangilao production wells. Mean decadal chloride concentrations were the highest during the 2000s decade at all production wells. Excessive well bottom depths are a concern in the Mangilao Basin, especially given the lack of monitoring wells to evaluate the prime layer and 50% seawater isochlor depths.

**Yigo-Tumon Basin**

In the Yigo-Tumon Basin, chloride concentrations only exceed 150 mg/l at six of the 79 production wells, and only exceed 250 mg/l at three production wells (D-8, D-13 and D-26). However, significantly increasing chloride trends occur at 75% of the Yigo-Tumon production wells. Mean decadal chloride concentrations were highest during the 2000s decade at 51 production wells, 37 of which experienced their highest mean decadal pump rates during this decade. Excessive well bottom depths are also a concern in the Yigo-Tumon Basin in both the basal and para-basal groundwater zones. Similar to other basins, excessive pumping and well bottom depths, combined with an overall thinning of the freshwater lens from 2005 through 2010, are likely contributing to the increasing chloride concentrations.

## 6.2 Relative Contribution of Hydrologic Variables to NGLA Salinity

**Rainfall**

Below-average total annual rainfall is probably the main contributor to the thinning freshwater lens from 2005 through 2010. Reduced rainfall equals reduced recharge to the aquifer, assuming that runoff, discharge, and evapotranspiration remain constant. Since 1973, the cumulative effect of several consecutive years of below-average or above-average rainfall appears to have a greater effect on groundwater salinity (based on chloride trends) than one isolated anomalous year. Inferred 50% seawater isochlor depths using hydraulic head data indicate that the freshwater lens was thinner historically than it was at its thinnest point from 2005 through 2010. Increasing chloride concentrations at many production wells, such as at basal production well A-10 (Figure 24a) and para-basal production well A-1 (Figure 24b) coincide with this period of reduced rainfall and freshwater lens thinning. This study only evaluated groundwater chloride concentrations with mean annual and seasonal rainfall amounts at one rain station; therefore, further study should evaluate groundwater chloride concentrations with Guam's rainfall at multiple stations and shorter timeframes. Additional study of the mass balance of chloride throughout the hydrologic cycle on northern Guam, and from man-made chloride sources if possible, should be a high priority given the increasing chloride concentrations at most NGLA production wells, but especially those within the supra-basal groundwater zone.

**Mean Sea Level**

Mean sea levels at Apra Harbor exhibit an increasing trend since 1960, with a sharper gradient occurring between 1990 and 2010. The MSL rise observed on Guam follows a global trend of increasing sea levels. Notably, during the past two decades when sea level rise at Apra Harbor appears sharper, chloride concentrations show an overall increase, with increased variability and increasing magnitude in the cyclical peaks at many NGLA production wells. At basal production well A-10, chloride concentrations followed the rise and fall of the MSL measurements. The effects of sea level rise on saltwater intrusion into coastal and island aquifers are of current scientific study and modeling. This study shows a correlation between chloride concentrations and local sea level rise and fall that should be studied further, particularly to closely evaluate all the NGLA wells and at a finer scale than monthly MSL.

**El Niño / Southern Oscillation**

The cyclical chloride trend at basal production well M-6 appears to correspond to transitions to and from El Niño and La Niña episodes at times, but not consistently over the entire time period. La Niña episodes, which are noted for very high sea levels in the Pacific Ocean, exhibit stronger Pacific trade winds capable of carrying increased amounts of salt aerosols that serve as condensation nuclei for rainfall, and contribute dry salt deposits to the land surface. Increased wave activity and sea spray along the coastline may also add dry salt deposits across Guam. Diffuse or fast-flow recharge, with concomitant infiltration of dissolved salts, can occur on the order of months to hours, respectively, depending on the intensity and amount of rainfall (Jocson et al., 2002). Conversely, one might expect chloride concentrations in groundwater to decrease during transitions from La Niña to El Niño, as Pacific trade winds and regional sea levels subside and rainfall is often abundant. This study did not compare the SOI to all of the NGLA production well chloride trends. Additional study of the relationship between ENSO and NGLA salinity conditions is recommended.

## 6.3 Aquifer Management Recommendations

The recommendations provided below are intended to improve the understanding and management of the NGLA based on information compiled and analyzed during this salinity study.

1. Regular analysis of production well samples for chlorides has been the long-standing method of monitoring groundwater salinity in the NGLA. Chloride benchmarks established in the 1982 NGLS and modified by McDonald and Jenson (2003) are suggestive of particular groundwater zones or saltwater up-coning occurrence, which may or may not be appropriate. Therefore, this study proposes a revised chloride benchmark terminology that reflects groundwater quality rather than location, is non-interpretive, and should be more useful for groundwater resource managers.

2. Documentation of the well bottom depth and screened interval is vital to proper management of the production wells. These data gaps should be addressed by locating the well construction documentation, or by using down-hole cameras or measuring devices to identify the well bottom and screen interval depths at those specific production wells.

3. The wellhead elevations at all active production wells should be professionally surveyed to a common datum in order to create an NGLA groundwater contour map, similar to what was produced in the 1982 NGLS. Well-head elevation discrepancies exist in well construction and maintenance records for numerous NGLA production wells.

4. Given the seasonal thinning of the potable layer during the dry season (January to June) and elevated chloride concentrations in the southeast region of the Hagåtña basin, decreased pumping rates are recommended during the dry season at production wells A-9, A-10, A-13, A-14, A-17, A-18, A-19, A-21, and A-28.

Increasing chlorides at production well A-4 should be monitored closely and ultimately should be added to this list if concentrations reach the "Marginal" benchmark.

5. The NGLS well design guidelines should continue to be used for groundwater management purposes. All attempts should be made to adhere to the recommended pump rate guidelines. A definition of "special conditions" should be created to explicitly outline when the para-basal production wells in the Hagåtña Basin can be pumped at 350 gpm, as opposed to the recommended limit of 200 gpm. Additionally, the special considerations for the "upper Yigo Basin" should be re-evaluated, especially if production wells in this area are allowed increased pump rates and deeper well depths.
6. Guidelines should be established for well bottom depth and maximum pump rate at production wells situated in the supra-basal groundwater zone.
7. The saltwater toe should be established as a separate groundwater zone given its elevated and fluctuating salinity conditions. Production wells situated in the saltwater toe zone, close to the minus 40-meter volcanic basement contour in all groundwater basins except the southern Hagåtña Basin (minus 80-meter volcanic basement contour), should be evaluated for special management considerations.
8. Deep monitoring wells should be installed within the Finegayan, Andersen and Mangilao Basins, as well as at the headwaters of the Yigo-Tumon trough near production wells Y-3, Y-7 and Y-9, and within the Marianas Bonin Command (MARBO) well field where production wells AFMW-5/5A through AFMW-9/9A are located. The deep monitoring wells should, at a minimum, intersect the 50% seawater isochlor and ideally encounter the volcanic basement to update the volcanic basement contour map.
9. The fullest extent of seasonal fluctuation of the prime layer in the Hagåtña Basin may not be captured with the quarterly salinity profiles. Dedicated CTD probes, or increased frequency of obtaining salinity profiles, are recommended at EX-1 and EX-4 in the Hagåtña Basin to monitor the seasonal fluctuations of the prime layer and 50% seawater isochlor. Quarterly salinity profiles at monitoring wells EX-6, EX-7, EX-9, EX-10 and GHURA-DEDEDO should suffice for monitoring the salinity of the other five basins, with additional consideration for monitoring wells EX-8 and AECOM-9.
10. A chloride mass balance study over an extended timeframe, ideally 5-6 years to capture the ENSO cycle, is recommended to understand the flux of chloride throughout the hydrologic cycle on northern Guam, incorporating rainfall, surface water, groundwater, and seawater samples.
11. Further analysis of man-made sources of chloride is recommended, particularly from septic system leaks, industrial processes, agricultural processes, and chlorine-treated water leaks from the potable water supply distribution system.
12. Hydraulic head and drawdown measurements should be documented at all NGLA production wells on a routine basis. This is particularly important during the dry

season or during prolonged periods of reduced rainfall when the freshwater lens may be thinning.

13. Annual groundwater status reports, summarizing the available groundwater quality data collected from GWA, NAVFACMAR, private well owners, Guam EPA, and USGS/WERI for any given 12-month period, should be prepared and made available to the various agencies involved in groundwater management within the NGLA.

14. Given the focus of this study on hydrologic and management variables as potential contributors to aquifer salinity, future studies should also consider the effects of other natural factors, such as karst features (i.e. sinkholes) and structural elements (i.e. faults), as well as human factors, such as population growth and land use, to salinity conditions within the NGLA.

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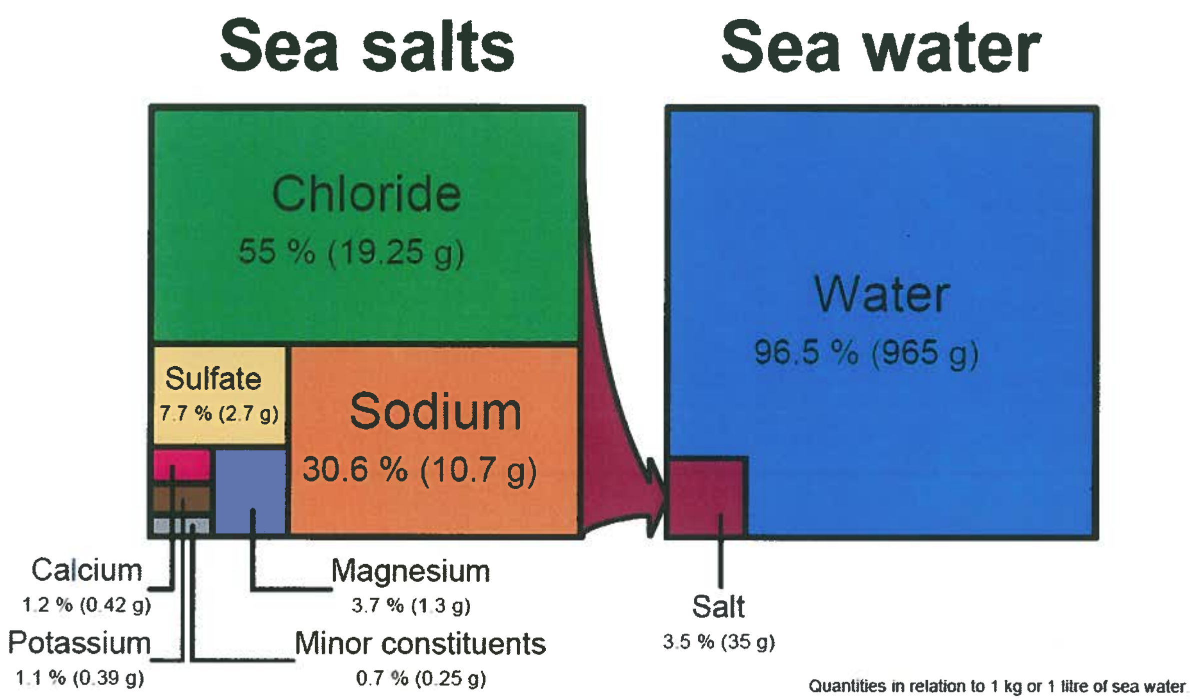
## APPENDICES

### Appendix A.

**Diagram of seawater salt ions** (from Wikipedia: Seawater)

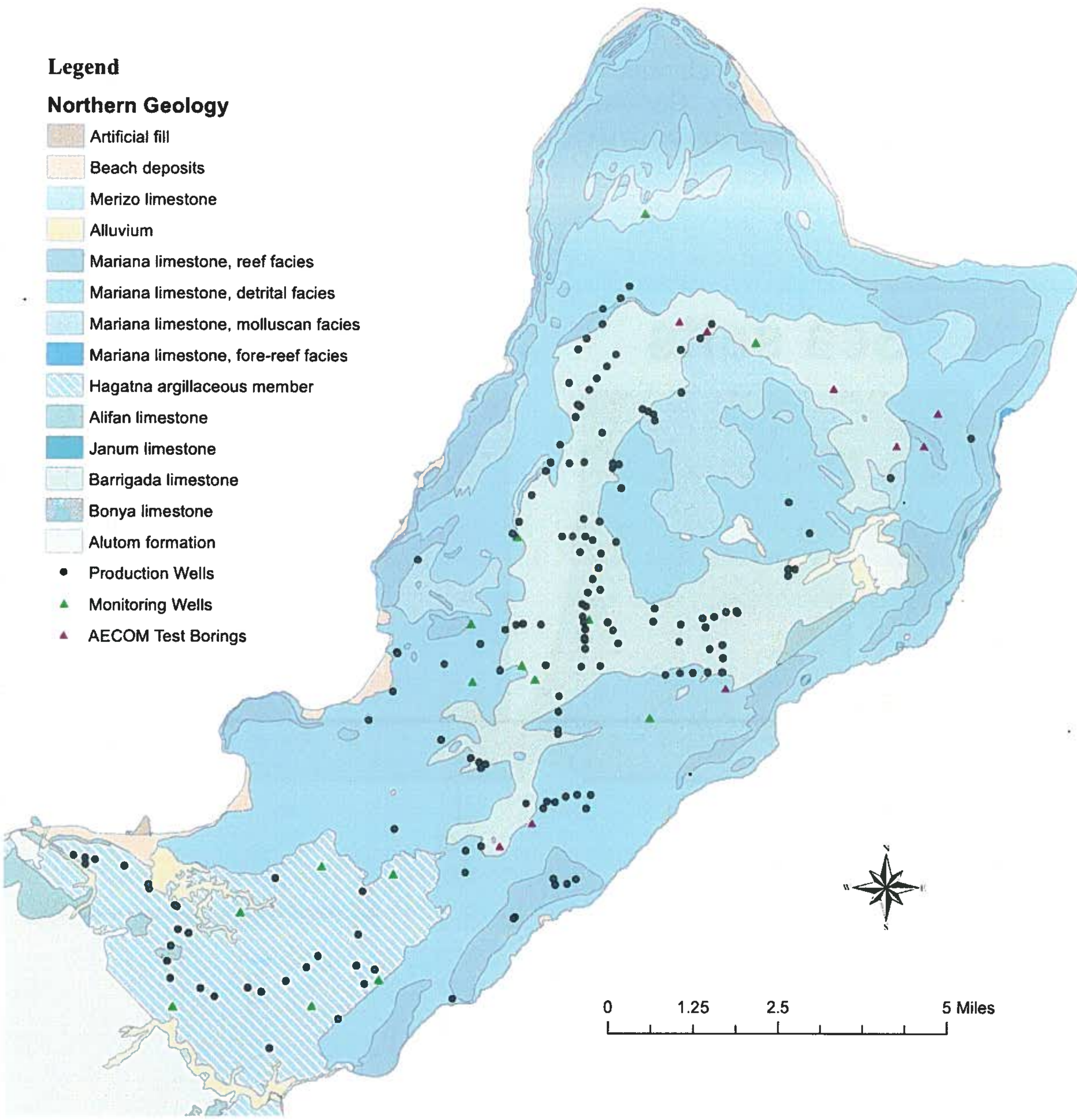
Even though salinity (the total concentration of dissolved ions) may vary, the proportions of the constituents remain uniform throughout the oceans. Because chloride is abundant (more than half of the total mass of salts), and chloride concentration can be readily measured (e.g., by titration, ion chromatography), chloride concentration (expressed in mg/l or ppm) is the most widely used index of salinity. One-hundred percent seawater is thus indicated by 19,250 mg/l chloride; 50% seawater equivalent is 9,625 mg/l chloride.



# Appendix B.

## Map of wells in relation to surface geology of northern Guam

Map after Siegrist & Regan 2008. Well data from AECOM 2011, USGS website, GWA data.

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## Appendix C

## Linear regression analysis of chloride data at NGLA production wells

Linear regression results of chloride, *y*, over time, *x*, in months for all production wells for which reliable records exist. Graphs of regression lines are in Appendix F.

| Well ID | Linear Regression Eq. | r | r (crit) * | df | Result | Trend |
|---|---|---|---|---|---|---|
| D26 | y = 0.0931x - 3404.6 | 0.923 | 0.404 | 22 | Significant | Increase |
| D27 | y = 0.0092x - 328.43 | 0.547 | 0.388 | 24 | Significant | Increase |
| D28 | y = 0.0125x - 424.68 | 0.579 | 0.381 | 25 | Significant | Increase |
| EX05A | y = 0.033x - 69.356 | 0.727 | 0.196 | 99 | Significant | Increase |
| EX11 | y = 0.0037x - 78.573 | 0.540 | 0.195 | 101 | Significant | Increase |
| F01 | y = 0.0068x - 120.57 | 0.728 | 0.138 | 212 | Significant | Increase |
| F02 | y = 0.0036x + 1.7442 | 0.556 | 0.138 | 200 | Significant | Increase |
| F03 | y = 0.0027x + 20.168 | 0.440 | 0.138 | 197 | Significant | Increase |
| F04 | y = 0.0104x - 195.95 | 0.600 | 0.142 | 189 | Significant | Increase |
| F05 | y = 0.0082x - 184.03 | 0.759 | 0.142 | 190 | Significant | Increase |
| F06 | y = 0.0202x - 451.23 | 0.700 | 0.142 | 186 | Significant | Increase |
| F07 | y = 0.0073x - 157.22 | 0.822 | 0.142 | 192 | Significant | Increase |
| F08 | y = 0.0031x - 70.405 | 0.624 | 0.145 | 180 | Significant | Increase |
| F09 | y = 0.0029x - 26.004 | 0.418 | 0.159 | 153 | Significant | Increase |
| F10 | y = 0.0151x - 305.23 | 0.637 | 0.159 | 148 | Significant | Increase |
| F11 | y = 0.0075x - 119.99 | 0.629 | 0.159 | 153 | Significant | Increase |
| F12 | y = 0.0043x - 122.37 | 0.295 | 0.223 | 76 | Significant | Increase |
| F13 | y = 0.007x - 20.115 | 0.153 | 0.261 | 55 | Not significant | Increase |
| F15 | y = 0.0008x + 29.783 | 0.064 | 0.252 | 59 | Not significant | Increase |
| F16 | y = 0.0046x - 139.84 | 0.572 | 0.257 | 57 | Significant | Increase |
| F17 | y = 0.0038x - 116.87 | 0.489 | 0.271 | 51 | Significant | Increase |
| F18 | y = 0.0032x - 92.036 | 0.340 | 0.271 | 51 | Significant | Increase |
| F19 | y = 0.069x - 2448.3 | 0.721 | 0.404 | 22 | Significant | Increase |
| F20 | y = 0.0913x - 3307.5 | 0.795 | 0.381 | 25 | Significant | Increase |
| G501 | y = 0.0113x - 290.16 | 0.734 | 0.190 | 103 | Significant | Increase |
| H01 | y = 0.0085x - 159.71 | 0.912 | 0.145 | 181 | Significant | Increase |
| HGC2 | y = 0.0037x - 105.68 | 0.636 | 0.235 | 68 | Significant | Increase |
| M01 | y = 0.0027x + 72.257 | 0.301 | 0.138 | 215 | Significant | Increase |
| M02 | y = 0.0052x - 74.207 | 0.620 | 0.138 | 211 | Significant | Increase |
| M03 | y = 0.002x - 35.157 | 0.620 | 0.138 | 216 | Significant | Increase |
| M04 | y = 0.0019x - 33.952 | 0.653 | 0.138 | 218 | Significant | Increase |
| M05 | y = 0.0028x - 38.654 | 0.766 | 0.138 | 212 | Significant | Increase |
| M06 | y = 0.006x - 111.31 | 0.529 | 0.138 | 211 | Significant | Increase |
| M07 | y = 0.0018x - 18.025 | 0.654 | 0.138 | 205 | Significant | Increase |
| M08 | y = 0.0019x - 34.678 | 0.661 | 0.138 | 217 | Significant | Increase |
| M09 | y = 0.0039x + 326.05 | 0.224 | 0.138 | 208 | Significant | Increase |
| M12 | y = 0.0045x - 61.769 | 0.544 | 0.145 | 177 | Significant | Increase |
| M14 | y = 0.0019x - 18.478 | 0.311 | 0.150 | 174 | Significant | Increase |
| M15 | y = 0.005x - 118.59 | 0.533 | 0.182 | 113 | Significant | Increase |
| M17A | y = 0.0025x - 13.049 | 0.164 | 0.291 | 44 | Not significant | Increase |
| M17B | y = 0.0009x + 33.361 | 0.124 | 0.220 | 78 | Not significant | Increase |
| M18 | y = 0.0041x - 85.835 | 0.386 | 0.276 | 49 | Significant | Increase |
| M20A | y = 0.0005x + 61.931 | 0.029 | 0.266 | 53 | Not significant | Increase |
| M21 | y = 0.0026x + 7.1158 | 0.102 | 0.301 | 41 | Not significant | Increase |
| M23 | y = -0.0003x + 65.548 | 0.016 | 0.320 | 36 | Not significant | Decrease |
| NAS1 | y = 0.0222x - 745.95 | 0.595 | 0.316 | 37 | Significant | Increase |
| Y01 | y = 0.0013x - 17.724 | 0.650 | 0.138 | 218 | Significant | Increase |
| Y02 | y = 0.0015x - 23.43 | 0.643 | 0.138 | 216 | Significant | Increase |
| Y03 | y = 0.0014x - 21.045 | 0.624 | 0.138 | 214 | Significant | Increase |
| Y04A | y = 0.0016x - 25.771 | 0.733 | 0.150 | 174 | Significant | Increase |
| Y05 | y = 0.0043x - 96.24 | 0.807 | 0.154 | 155 | Significant | Increase |
| Y06 | y = 0.0016x - 27.024 | 0.564 | 0.165 | 140 | Significant | Increase |

Linear Regression Analysis (continued)

| Well ID | Linear Regression Eq. | r | r (crit) * | df | Result | Trend |
|---|---|---|---|---|---|---|
| Y07 | y = 0.0012x - 16.621 | 0.489 | 0.215 | 82 | Significant | Increase |
| Y09 | y = 0.0029x - 76.239 | 0.735 | 0.209 | 87 | Significant | Increase |
| Y10 | y = 0.0053x - 149.12 | 0.568 | 0.291 | 44 | Significant | Increase |
| Y12 | y = 0.005x - 123.15 | 0.551 | 0.266 | 53 | Significant | Increase |
| Y14 | y = 0.0041x - 105.3 | 0.563 | 0.482 | 15 | Significant | Increase |
| Y15 | y = 0.0031x - 83.955 | 0.488 | 0.257 | 57 | Significant | Increase |
| Y16 | y = -0.001x + 86.247 | 0.096 | 0.320 | 36 | Not significant | Decrease |
| Y17 | y = 0.0014x - 19.11 | 0.151 | 0.344 | 31 | Not significant | Increase |
| Y18 | y = 0.0115x - 415.61 | 0.844 | 0.396 | 23 | Significant | Increase |
| Y19 | y = 0.0053x - 160.42 | 0.334 | 0.381 | 25 | Not significant | Increase |
| Y20 | y = 0.0122x - 437.17 | 0.808 | 0.388 | 24 | Significant | Increase |
| Y21A | y = -0.0019x + 126.09 | 0.127 | 0.325 | 35 | Not significant | Decrease |
| Y22 | y = 0.0057x - 193.14 | 0.580 | 0.388 | 24 | Significant | Increase |
| Y23 | y = -0.0024x + 133.57 | 0.244 | 0.339 | 32 | Not significant | Decrease |
| AFMW-1 | y = 0.0012x + 6.1461 | 0.384 | 0.304 | 38 | Significant | Increase |
| AFMW-2 | y = -0.0007x + 65.769 | 0.102 | 0.381 | 25 | Not significant | Decrease |
| AFMW-3 | y = 0.00008 + 25.179 | 0.041 | 0.367 | 27 | Not significant | Increase |
| AFMW-5 | y = 0.0007x + 26.51 | 0.150 | 0.381 | 25 | Not significant | Increase |
| AFMW-6 | y = 0.0026x - 30.449 | 0.555 | 0.396 | 23 | Significant | Increase |
| AFMW-7 | y = 0.0013x + 0.321 | 0.378 | 0.361 | 28 | Significant | Increase |
| AFMW-8 | y = 0.0011x + 6.6849 | 0.237 | 0.404 | 22 | Not significant | Increase |
| AFMW-9 | y = 0.002x - 20.956 | 0.626 | 0.329 | 34 | Significant | Increase |
| BPM-1 | y = -0.0014x + 76.304 | 0.241 | 0.811 | 4 | Not significant | Decrease |
| TMT | y = 0.0004x + 65.878 | 0.088 | 0.355 | 29 | Not significant | Increase |
| NCS A | y = -0.01x + 632.14 | 0.177 | 0.159 | 153 | Significant | Decrease |
| NCS B | y = -0.016x + 682.83 | 0.433 | 0.232 | 70 | Significant | Decrease |
| NCS-2 | y = 0.0194x - 553.53 | 0.337 | 0.205 | 90 | Significant | Increase |
| NCS-3 | y = 0.0038x + 26.63 | 0.092 | 0.174 | 124 | Not significant | Increase |
| NCS-5 | y = -0.0354x + 1506.9 | 0.467 | 0.171 | 127 | Significant | Decrease |
| NCS-6 | y = 0.0006x + 40.407 | 0.048 | 0.154 | 159 | Not significant | Increase |
| NCS-7 | y = -0.0002x + 49.054 | 0.020 | 0.159 | 153 | Not significant | Decrease |
| NCS-8 | y = 0.0103x - 284.65 | 0.210 | 0.235 | 68 | Not significant | Increase |
| NCS-9 | y = 0.0026x - 1.6156 | 0.137 | 0.162 | 143 | Not significant | Increase |
| NCS-10 | y = 0.0458x - 1646.5 | 0.608 | 0.344 | 31 | Significant | Increase |
| NCS-11 | y = -0.0088x + 438.08 | 0.333 | 0.367 | 27 | Not significant | Decrease |
| NCS-12 | y = 0.0255x - 930.56 | 0.569 | 0.349 | 30 | Significant | Increase |
| NRMC 1 | y = -0.0008x + 58.179 | 0.094 | 0.150 | 170 | Not significant | Decrease |
| NRMC 2 | y = -0.0115x + 503.12 | 0.201 | 0.152 | 165 | Significant | Decrease |
| NRMC 3 | y = -0.0022x + 141.05 | 0.044 | 0.159 | 152 | Not significant | Decrease |
| FM-1A | y = 0.3738x +121.21 | 0.098 | 0.576 | 10 | Not significant | Increase |
| GPH-1 | y = -04795x + 85.528 | 0.263 | 0.95 | 2 | Not significant | Decrease |
| GPH-2 | y = 0.65x + 76.8 | 0.180 | 0.997 | 1 | Not significant | Increase |
| HGC-3 | y = 0.3014x + 11.376 | 0.370 | 0.666 | 7 | Not significant | Increase |
| HRP-1 | y = -2.5393x + 238.49 | 0.168 | 0.576 | 10 | Not significant | Decrease |
| HRP-2 | y = -1.5224x + 196.15 | 0.262 | 0.602 | 9 | Not significant | Decrease |
| MGC-1 | y = -15.837x + 319.9 | 0.520 | 0.755 | 5 | Not significant | Decrease |
| MGC-2 | y = -11.095x + 283.05 | 0.559 | 0.878 | 3 | Not significant | Decrease |
| MGC-4 | y = -13.28x + 232.65 | 0.873 | 0.707 | 6 | Significant | Decrease |
| PBI-1 | y = -2.0355x + 98.504 | 0.450 | 0.666 | 7 | Not significant | Decrease |

* - Values taken from Table B.17 in *Biostatistical Analysis* (Zar 1999)

## Appendix D

### Estimated lower limit of prime layer at the deep monitoring wells

| Date | Approximate Lower Limit of the Prime Layer in NGLA Monitoring Wells | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EX-1 | | EX-4 | | EX-6 | | EX-7 | | EX-9 | | EX-10 | | Ghura-Dededo | |
| | feet | meters | feet | meters | feet | meters | feet | meters | feet | meters | feet | meters | feet | meters |
| May-05 | NA | NA | NA | NA | -139.97 | -42.66 | -120.07 | -36.60 | NA | NA | -107.25 | -32.69 | NA | NA |
| Aug-05 | -168.31 | -51.30 | -62.34 | -19.00 | -139.73 | -42.59 | -120.64 | -36.77 | -100.07 | -30.50 | -108.09 | -32.95 | -129.22 | -39.39 |
| Dec-05 | -142.89 | -43.55 | -239.20 | -72.91 | -139.90 | -42.64 | -118.84 | -36.22 | -99.36 | -30.28 | -105.90 | -32.28 | -131.59 | -40.11 |
| Feb-06 | -68.82 | -20.98 | -13.73 | -4.18 | -140.00 | -42.67 | -119.34 | -36.37 | -100.59 | -30.66 | -105.63 | -32.20 | -128.94 | -39.30 |
| May-06 | -56.97 | -17.36 | NA | NA | -138.96 | -42.36 | -116.37 | -35.47 | -95.88 | -29.22 | -105.91 | -32.28 | -125.94 | -38.39 |
| Aug-06 | -167.47 | -51.04 | -146.81 | -44.75 | -138.66 | -42.26 | -114.93 | -35.03 | -96.34 | -29.36 | -105.03 | -32.01 | -125.79 | -38.34 |
| Nov-06 | -144.40 | -44.01 | -176.24 | -53.72 | -138.39 | -42.18 | -115.49 | -35.20 | -96.16 | -29.31 | -104.28 | -31.78 | -126.48 | -38.55 |
| Mar-07 | -70.70 | -21.55 | -12.62 | -3.85 | -136.56 | -41.62 | -117.47 | -35.80 | -95.70 | -29.17 | -103.21 | -31.46 | -124.29 | -37.88 |
| Jun-07 | -58.89 | -17.95 | -11.72 | -3.57 | -134.74 | -41.07 | -116.43 | -35.49 | -92.41 | -28.17 | -102.45 | -31.23 | -118.81 | -36.21 |
| Sep-07 | -146.13 | -44.54 | -151.79 | -46.27 | -136.00 | -41.45 | -114.99 | -35.05 | -90.78 | -27.67 | -100.89 | -30.75 | -120.06 | -36.59 |
| Dec-07 | -187.85 | -57.26 | -230.17 | -70.16 | -134.29 | -40.93 | NA | NA | -90.93 | -27.72 | NA | NA | -120.38 | -36.69 |
| Mar-08 | -136.55 | -41.62 | -14.19 | -4.33 | -133.96 | -40.83 | -114.23 | -34.82 | -92.37 | -28.15 | -101.12 | -30.82 | -118.82 | -36.22 |
| Jun-08 | -56.64 | -17.26 | -9.58 | -2.92 | -130.55 | -39.79 | -111.01 | -33.84 | -90.52 | -27.59 | -99.55 | -30.34 | -112.35 | -34.24 |
| Sep-08 | -110.85 | -33.79 | -133.28 | -40.62 | -130.56 | -39.79 | -105.63 | -32.20 | -86.70 | -26.43 | -97.19 | -29.62 | -112.04 | -34.15 |
| Dec-08 | -61.46 | -18.73 | NA | NA | NA | NA | -95.56 | -29.13 | -85.59 | -26.09 | -95.05 | -28.97 | -111.63 | -34.02 |
| Feb-09 | -59.45 | -18.12 | NA | NA | NA | NA | -93.44 | -28.48 | -85.49 | -26.06 | -95.65 | -29.15 | -111.61 | -34.02 |
| Jun-09 | -57.37 | -17.49 | NA | NA | NA | NA | -93.05 | -28.36 | -85.20 | -25.97 | -95.17 | -29.01 | -111.63 | -34.02 |
| Oct-09 | -198.47 | -60.49 | -231.96 | -70.70 | NA | NA | -94.68 | -28.86 | -86.79 | -26.45 | -94.50 | -28.80 | -113.07 | -34.46 |
| Dec-09 | -112.78 | -34.38 | -134.41 | -40.97 | NA | NA | -92.31 | -28.14 | -88.59 | -27.00 | -93.84 | -28.60 | -112.00 | -34.14 |
| Feb-10 | -110.96 | -33.82 | -14.07 | -4.29 | NA | NA | -97.85 | -29.82 | -89.42 | -27.26 | -94.28 | -28.74 | -112.19 | -34.20 |
| Jun-10 | -56.37 | -17.18 | -10.49 | -3.20 | NA | NA | -96.21 | -29.32 | -86.73 | -26.44 | -95.29 | -29.04 | -112.09 | -34.17 |
| Oct-10 | -159.79 | -48.70 | -174.84 | -53.29 | NA | NA | -96.60 | -29.44 | -85.70 | -26.12 | -96.24 | -29.33 | -113.45 | -34.58 |

Approximated elevations of base of prime layer (1100 µS/cm, 250 mg/l Cl-) based on data from deep monitoring wells.
Data source: USGS website.

## Appendix E

## Comparison of 50% seawater isochlor depths from salinity profiles and Ghyben-Herzberg estimates at the NGLA deep monitoring wells

Summary of salinity data obtained from the NGLA deep monitoring well quarterly from May 2005 to October 2010. This data table compares the measured 50% seawater isochlor depth (depth where specific conductance value closest to 27,000 µS/cm) with the estimated 50% seawater isochlor depth applying the Ghyben-Herzberg 40:1 ratio to the hydraulic head measurements collected concurrently with the salinity profiles; the difference between the two depths for each monitoring event is noted. The last column lists the ratio of the 50% seawater isochlor depth to hydraulic head measurements (note most ratios were less than the 40:1 Ghyben-Herzberg relation; NA – not applicable).

| Date | EX-4 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 50% Isochlor in Salinity Profiles | | Head | 50% Isochlor using Ghyben-Herzberg( 40:1) | | Difference | | Measured Ratio to 50% Isochlor |
| | feet | meters | feet | feet | meters | feet | meters | |
| May-05 | > 240 | > -73.15 | 6.00 | -240.00 | -73.15 | NA | NA | NA |
| Aug-05 | -239.38 | -72.96 | 6.40 | -256.00 | -78.03 | 5.07 | 5.07 | 37.40 |
| Dec-05 | > 240 | > -73.15 | 6.94 | -277.60 | -84.61 | NA | NA | NA |
| Feb-06 | > 240 | > -73.15 | 6.10 | -244.00 | -74.37 | NA | NA | NA |
| May-06 | > 240 | > -73.15 | 6.05 | -242.00 | -73.76 | NA | NA | NA |
| Aug-06 | > 240 | > -73.15 | 6.67 | -266.80 | -81.32 | NA | NA | NA |
| Nov-06 | > 240 | > -73.15 | 6.61 | -264.40 | -80.59 | NA | NA | NA |
| Mar-07 | > 240 | > -73.15 | 5.77 | -230.80 | -70.35 | NA | NA | NA |
| Jun-07 | -238.71 | -72.76 | 5.53 | -221.20 | -67.42 | 5.34 | 5.34 | 43.17 |
| Sep-07 | -237.42 | -72.37 | 6.16 | -246.40 | -75.10 | 2.74 | 2.74 | 38.54 |
| Dec-07 | > 240 | > -73.15 | 6.91 | -276.40 | -84.25 | NA | NA | NA |
| Mar-08 | -238.65 | -72.74 | 6.27 | -250.80 | -76.44 | 3.70 | 3.70 | 38.06 |
| Jun-08 | -236.19 | -71.99 | 5.72 | -228.80 | -69.74 | 2.25 | 2.25 | 41.29 |
| Sep-08 | -233.65 | -71.22 | 6.04 | -241.60 | -73.64 | 2.42 | 2.42 | 38.68 |
| Dec-08 | -233.25 | -71.09 | 5.97 | -238.80 | -72.79 | 1.69 | 1.69 | 39.07 |
| Feb-09 | -232.17 | -70.77 | 5.81 | -232.40 | -70.84 | 0.07 | 0.07 | 39.96 |
| Jun-09 | -225.4 | -68.70 | 5.24 | -209.60 | -63.89 | 4.82 | 4.82 | 43.02 |
| Oct-09 | -234.64 | -71.52 | 7.30 | -292.00 | -89.00 | 17.48 | 17.48 | 32.14 |
| Dec-09 | -231.65 | -70.61 | 6.29 | -251.60 | -76.69 | 6.08 | 6.08 | 36.83 |
| Feb-10 | -231.74 | -70.63 | 5.76 | -230.40 | -70.23 | 1.34 | 0.41 | 40.23 |
| Jun-10 | -224.9 | -68.55 | 5.32 | -212.80 | -64.86 | 12.10 | 3.69 | 42.27 |
| Oct-10 | -226.82 | -69.13 | 6.21 | -248.40 | -75.71 | 21.58 | 6.58 | 36.52 |

| Date | EX-6 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 50% Isochlor in Salinity Profiles | | Head | 50% Isochlor using Ghyben-Herzberg( 40:1) | | Difference | | Measured Ratio to 50% Isochlor |
| | feet | meters | feet | feet | meters | feet | meters | |
| May-05 | > -140 | > -42.67 | 4.40 | -176.00 | -53.64 | NA | NA | NA |
| Aug-05 | > -140 | > -42.67 | 4.30 | -172.00 | -52.43 | NA | NA | NA |
| Dec-05 | > -140 | > -42.67 | 3.75 | -150.00 | -45.72 | NA | NA | NA |
| Feb-06 | > -140 | > -42.67 | 3.62 | -144.80 | -44.14 | NA | NA | NA |
| May-06 | > -140 | > -42.67 | 3.98 | -159.20 | -48.52 | NA | NA | NA |
| Aug-06 | > -140 | > -42.67 | 4.03 | -161.20 | -49.13 | NA | NA | NA |
| Nov-06 | -139.87 | -42.63 | 3.47 | -138.80 | -42.31 | 1.07 | 0.33 | 40.31 |
| Mar-07 | -139.82 | -42.62 | 3.40 | -136.00 | -41.45 | 3.82 | 1.16 | 41.12 |
| Jun-07 | -138.45 | NA | 3.47 | -138.80 | -42.31 | NA | NA | 39.90 |
| Sep-07 | -138.76 | -42.29 | 3.67 | -146.80 | -44.74 | 8.04 | 2.45 | 37.81 |
| Dec-07 | -138.37 | -42.18 | 3.66 | -146.40 | -44.62 | 8.03 | 2.45 | 37.81 |
| Mar-08 | -138.62 | -42.25 | 3.85 | -154.00 | -46.94 | 15.38 | 4.69 | 36.01 |
| Jun-08 | -133.82 | -40.79 | 3.89 | -155.60 | -47.43 | 21.78 | 6.64 | 34.40 |
| Sep-08 | -133.44 | -40.67 | 3.88 | -155.20 | -47.30 | 21.76 | 6.63 | 34.39 |
| Dec-08 | NA | NA | NA | NA | NA | NA | NA | NA |
| Feb-09 | NA | NA | NA | NA | NA | NA | NA | NA |
| Jun-09 | NA | NA | NA | NA | NA | NA | NA | NA |
| Oct-09 | NA | NA | NA | NA | NA | NA | NA | NA |
| Dec-09 | NA | NA | NA | NA | NA | NA | NA | NA |
| Feb-10 | NA | NA | NA | NA | NA | NA | NA | NA |
| Jun-10 | NA | NA | NA | NA | NA | NA | NA | NA |
| Oct-10 | NA | NA | NA | NA | NA | NA | NA | NA |

| Date | EX-7 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 50% Isochlor in Salinity Profiles | | Head | 50% Isochlor using Ghyben-Herzberg( 40:1) | | Difference | | Measured Ratio to 50% Isochlor |
| | feet | meters | feet | feet | meters | feet | meters | |
| May-05 | -128.88 | -39.28 | 3.00 | -120.00 | -36.58 | 8.88 | 2.71 | NA |
| Aug-05 | -130.64 | -39.82 | 3.90 | -156.00 | -47.55 | 25.36 | 7.73 | 33.50 |
| Dec-05 | -127.81 | -38.96 | 3.51 | -140.40 | -42.79 | 12.59 | 3.84 | NA |
| Feb-06 | -128.06 | -39.03 | 3.43 | -137.20 | -41.82 | 9.14 | 2.79 | NA |
| May-06 | -127.43 | -38.84 | 3.81 | -152.40 | -46.45 | 24.97 | 7.61 | NA |
| Aug-06 | -128.74 | -39.24 | 3.94 | -157.60 | -48.04 | 28.86 | 8.80 | 32.68 |
| Nov-06 | -128.45 | -39.15 | 3.25 | -130.00 | -39.62 | 1.55 | 0.47 | NA |
| Mar-07 | -126.1 | -38.44 | 3.17 | -126.80 | -38.65 | 0.70 | 0.21 | 39.78 |
| Jun-07 | -124.45 | -37.93 | 3.33 | -133.20 | -40.60 | 8.75 | 2.67 | 37.37 |
| Sep-07 | -120.93 | -36.86 | 3.41 | -136.40 | -41.57 | 15.47 | 4.72 | 35.46 |
| Dec-07 | NA | NA | NA | NA | NA | NA | NA | NA |
| Mar-08 | -120.65 | -36.77 | 3.61 | -144.40 | -44.01 | 23.75 | 7.24 | 33.42 |
| Jun-08 | -120.63 | -36.77 | 3.78 | -151.20 | -46.09 | 30.57 | 9.32 | 31.91 |
| Sep-08 | -116.96 | -35.65 | 3.62 | -144.80 | -44.14 | 27.84 | 8.49 | 32.31 |
| Dec-08 | -115.91 | -35.33 | 3.64 | -145.60 | -44.38 | 29.69 | 9.05 | 31.84 |
| Feb-09 | -115.51 | -35.21 | 3.47 | -138.80 | -42.31 | 23.29 | 7.10 | 33.29 |
| Jun-09 | -115.84 | -35.31 | 3.20 | -128.00 | -39.01 | 12.16 | 3.71 | 36.20 |
| Oct-09 | -115.39 | -35.17 | 3.50 | -140.00 | -42.67 | 24.61 | 7.50 | 32.97 |
| Dec-09 | NA | NA | 3.54 | -141.60 | -43.16 | NA | NA | NA |
| Feb-10 | -114.82 | -35.00 | 3.33 | -133.20 | -40.60 | 18.38 | 5.60 | 34.48 |
| Jun-10 | -114.33 | -34.85 | 3.30 | -132.00 | -40.23 | 17.67 | 5.39 | 34.65 |
| Oct-10 | -115.86 | -35.31 | 3.38 | -135.20 | -41.21 | 19.34 | 5.89 | 34.28 |

| Date | EX-9 | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | 50% Isochlor in Salinity Profiles | | Head | 50% Isochlor using Ghyben-Herzberg( 40:1) | | Difference | | Measured Ratio to 50% Isochlor |
| | feet | meters | feet | feet | meters | feet | meters | |
| May-05 | NA | NA | NA | NA | NA | NA | NA | NA |
| Aug-05 | -133.56 | -40.71 | 4.2 | -168.00 | -51.21 | 34.44 | 10.50 | 31.80 |
| Dec-05 | -132.81 | -40.48 | 3.99 | -159.60 | -48.65 | 26.79 | 8.17 | 33.29 |
| Feb-06 | -132.7 | -40.45 | 3.85 | -154.00 | -46.94 | 21.30 | 6.49 | 34.47 |
| May-06 | -130.21 | -39.69 | 4.19 | -167.60 | -51.08 | 37.39 | 11.40 | 31.08 |
| Aug-06 | -130.78 | -39.86 | 4.34 | -173.60 | -52.91 | 42.82 | 13.05 | 30.13 |
| Nov-06 | -130.43 | -39.76 | 3.83 | -153.20 | -46.70 | 22.77 | 6.94 | 34.05 |
| Mar-07 | -127.75 | -38.94 | 3.67 | -146.80 | -44.74 | 19.05 | 5.81 | 34.81 |
| Jun-07 | -124.86 | -38.06 | 3.72 | -148.80 | -45.35 | 23.94 | 7.30 | 33.56 |
| Sep-07 | -124.49 | -37.94 | 3.87 | -154.80 | -47.18 | 30.31 | 9.24 | 32.17 |
| Dec-07 | -125.44 | -38.23 | 3.96 | -158.40 | -48.28 | 32.96 | 10.05 | 31.68 |
| Mar-08 | -123.84 | -37.75 | 4.12 | -164.80 | -50.23 | 40.96 | 12.48 | 30.06 |
| Jun-08 | -123.39 | -37.61 | 3.79 | -151.60 | -46.21 | 28.21 | 8.60 | 32.56 |
| Sep-08 | -119.77 | -36.51 | 3.73 | -149.20 | -45.48 | 29.43 | 8.97 | 32.11 |
| Dec-08 | -117.89 | -35.93 | 3.72 | -148.80 | -45.35 | 30.91 | 9.42 | 31.69 |
| Feb-09 | -117.53 | -35.82 | 3.67 | -146.80 | -44.74 | 29.27 | 8.92 | 32.02 |
| Jun-09 | -117.86 | -35.92 | 3.25 | -130.00 | -39.62 | 12.14 | 3.70 | 36.26 |
| Oct-09 | -117.52 | -35.82 | 3.63 | -145.20 | -44.26 | 27.68 | 8.44 | 32.37 |
| Dec-09 | -117.29 | -35.75 | 3.67 | -146.80 | -44.74 | 29.51 | 8.99 | 31.96 |
| Feb-10 | -116.53 | -35.52 | 3.33 | -133.20 | -40.60 | 16.67 | 5.08 | 34.99 |
| Jun-10 | -116.37 | -35.47 | 3.22 | -128.80 | -39.26 | 12.43 | 3.79 | 36.14 |
| Oct-10 | -115.06 | -35.07 | 3.43 | -137.20 | -41.82 | 22.14 | 6.75 | 33.55 |

| Date | EX-10 | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | 50% Isochlor in Salinity Profiles | | Head | 50% Isochlor using Ghyben-Herzberg( 40:1) | | Difference | | Measured Ratio to 50% Isochlor |
| | feet | meters | feet | feet | meters | feet | meters | |
| May-05 | -124.63 | -37.99 | 3.50 | -140.00 | -42.67 | 15.37 | 4.68 | 35.61 |
| Aug-05 | -125.94 | -38.39 | 3.20 | -128.00 | -39.01 | 2.06 | 0.63 | 39.36 |
| Dec-05 | -125.19 | -38.16 | 3.19 | -127.60 | -38.89 | 2.41 | 0.73 | 39.24 |
| Feb-06 | -123.83 | -37.74 | 3.42 | -136.80 | -41.70 | 12.97 | 3.95 | 36.21 |
| May-06 | -125.85 | -38.36 | 3.30 | -132.00 | -40.23 | 6.15 | 1.87 | 38.14 |
| Aug-06 | -124.62 | -37.98 | 2.90 | -116.00 | -35.36 | 8.62 | 2.63 | 42.97 |
| Nov-06 | -123.36 | -37.60 | 2.85 | -114.00 | -34.75 | 9.36 | 2.85 | 43.28 |
| Mar-07 | -121.95 | -37.17 | 3.02 | -120.80 | -36.82 | 1.15 | 0.35 | 40.38 |
| Jun-07 | -120.3 | -36.67 | 3.06 | -122.40 | -37.31 | 2.10 | 0.64 | 39.31 |
| Sep-07 | -121.36 | -36.99 | 3.33 | -133.20 | -40.60 | 11.84 | 3.61 | 36.44 |
| Dec-07 | NA | NA | NA | NA | NA | NA | NA | NA |
| Mar-08 | -119.25 | -36.35 | 3.33 | -133.20 | -40.60 | 13.95 | 4.25 | 35.81 |
| Jun-08 | -116.93 | -35.64 | 3.40 | -136.00 | -41.45 | 19.07 | 5.81 | 34.39 |
| Sep-08 | -114.84 | -35.00 | 3.31 | -132.40 | -40.36 | 17.56 | 5.35 | 34.69 |
| Dec-08 | -113.61 | -34.63 | 3.48 | -139.20 | -42.43 | 25.59 | 7.80 | 32.65 |
| Feb-09 | -112.97 | -34.43 | 3.36 | -134.40 | -40.97 | 21.43 | 6.53 | 33.62 |
| Jun-09 | -112.91 | -34.41 | 3.09 | -123.60 | -37.67 | 10.69 | 3.26 | 36.54 |
| Oct-09 | -112.59 | -34.32 | 3.13 | -125.20 | -38.16 | 12.61 | 3.84 | 35.97 |
| Dec-09 | -112.08 | -34.16 | 3.19 | -127.60 | -38.89 | 15.52 | 4.73 | 35.13 |
| Feb-10 | -112.18 | -34.19 | 3.04 | -121.60 | -37.06 | 9.42 | 2.87 | 36.90 |
| Jun-10 | -112.37 | -34.25 | 3.03 | -121.20 | -36.94 | 8.83 | 2.69 | 37.09 |
| Oct-10 | -112.62 | -34.33 | 3.14 | -125.60 | -38.28 | 12.98 | 3.96 | 35.87 |

| Date | GHURA-DEDEDO | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 50% Isochlor in Salinity Profiles | | Head | 50% Isochlor using Ghyben-Herzberg( 40:1) | | Difference | | Measured Ratio to 50% Isochlor |
| | feet | meters | feet | feet | meters | feet | meters | |
| May-05 | NA | NA | NA | NA | NA | NA | NA | NA |
| Aug-05 | -149.61 | -45.60 | 4.20 | -168.00 | -51.21 | 18.39 | 5.61 | 35.62 |
| Dec-05 | -148.54 | -45.27 | 3.68 | -147.20 | -44.87 | 1.34 | 0.41 | 40.36 |
| Feb-06 | -147.09 | -44.83 | 3.55 | -142.00 | -43.28 | 5.09 | 1.55 | 41.43 |
| May-06 | -144.69 | -44.10 | 3.90 | -156.00 | -47.55 | 11.31 | 3.45 | 37.10 |
| Aug-06 | -143.77 | -43.82 | 3.89 | -155.60 | -47.43 | 11.83 | 3.61 | 36.96 |
| Nov-06 | -142.42 | -43.41 | 3.29 | -131.60 | -40.11 | 10.82 | 3.30 | 43.29 |
| Mar-07 | -139.7 | -42.58 | 3.15 | -126.00 | -38.40 | 13.70 | 4.18 | 44.35 |
| Jun-07 | -139.01 | -42.37 | 3.33 | -133.20 | -40.60 | 5.81 | 1.77 | 41.74 |
| Sep-07 | -137.73 | -41.98 | 3.44 | -137.60 | -41.94 | 0.13 | 0.04 | 40.04 |
| Dec-07 | -136.22 | -41.52 | 3.43 | -137.20 | -41.82 | 0.98 | 0.30 | 39.71 |
| Mar-08 | -135.21 | -41.21 | 3.64 | -145.60 | -44.38 | 10.39 | 3.17 | 37.15 |
| Jun-08 | -131.78 | -40.17 | 3.82 | -152.80 | -46.57 | 21.02 | 6.41 | 34.50 |
| Sep-08 | -131.15 | -39.97 | 3.69 | -147.60 | -44.99 | 16.45 | 5.01 | 35.54 |
| Dec-08 | -130.89 | -39.90 | 3.74 | -149.60 | -45.60 | 18.71 | 5.70 | 35.00 |
| Feb-09 | -129.93 | -39.60 | 3.61 | -144.40 | -44.01 | 14.47 | 4.41 | 35.99 |
| Jun-09 | -127.98 | -39.01 | 3.38 | -135.20 | -41.21 | 7.22 | 2.20 | 37.86 |
| Oct-09 | -128.75 | -39.24 | 3.47 | -138.80 | -42.31 | 10.05 | 3.06 | 37.10 |
| Dec-09 | -127.99 | -39.01 | 3.46 | -138.40 | -42.18 | 10.41 | 3.17 | 36.99 |
| Feb-10 | -127.45 | -38.85 | 3.38 | -135.20 | -41.21 | 7.75 | 2.36 | 37.71 |
| Jun-10 | -127.98 | -39.01 | 3.31 | -132.40 | -40.36 | 4.42 | 1.35 | 38.66 |
| Oct-10 | -127.87 | -38.97 | 3.55 | -142.00 | -43.28 | 14.13 | 4.31 | 36.02 |

# Appendix F

## Chloride and production trends at NGLA production wells

Graphical presentation of chloride concentration and pumping trends at NGLA production wells from 1973 through 2014. Linear regression analysis of the chloride data is presented in Appendix C.

**See the Chloride Production database (CPDB), accessible from the GHS website, <http://www.guamhydrologicsurvey.com/CPDB/.index.php>.**