Dynamic Response of the Freshwater Lens to Nautral Variations in Recharge, Northern Guam Lens Aquifer, Yigo-Tumon Basin

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

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Abstract

The limestone aquifer of northern Guam supplies more than 90% of the island's drinking water. The quantity of groundwater available for extraction can be measured in terms of the freshwater lens thickness. Lens thickness can be measured directly from well salinity profiles and inferred indirectly from water levels. The amount of recharge that replenishes the aquifer depends primarily on seasonal and inter-annual changes in rainfall as well as on evapotranspiration, rainfall intensity, and infiltration pathways. Time series data were evaluated in order to determine lens response to recharge and drought. Lag time responses to variations in recharge were determined and can be used as an indicator of lens responsiveness. This project characterizes the response of the lens to natural climate variations, and documents lens and transition zone dynamics driven by both abundant recharge and extensive drought. It will provide an observational baseline against which the accuracy of past, present, and future modeling studies can be evaluated and by which future modeling studies can be reliably parameterized.

Key words: lens thickness, Yigo-Tumon Basin, Northern Guam Lens Aquifer, rainfall

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Chapter 1

INTRODUCTION

Guam is located at 13° 28' N, 144° 45' E and is the largest island of the Mariana Islands chain. The island is 30 mi (48 km) long and 4-12 mi (6.5-18.5 km) wide with a total area of 212 mi² (550 km²). The Philippines is 1,370 mi (2,220 km) to the west, and Japan is 1,740 mi (2,800 km) to the north-northwest. The Mariana Islands are high points of a submarine ridge and the Mariana Trench, a deep subduction zone, lies 62-100 mi (100-160 km) southwest (Figure 1.1.). A fringing reef encircles most of the island apart from a few coastline cliffs.



Figure 1.1. Guam, USA, Mariana Islands.

The limestone aquifer of northern Guam supplies more than 90% of the island's drinking water. As Guam prepares for economic growth, the demand for water from the aquifer is a major concern. This research project uses historical groundwater hydrographic data and local meteorological data to study how the thickness, and hence the volume, of the freshwater lens in the Yigo-Tumon Basin responds to natural changes in recharge. The Yigo-Tumon Basin is the largest of the aquifer's six basins (Figure 1.2.), supplying 18 mgd, or 56%, of the total production of 33 mgd from the Northern Guam Lens Aquifer (NGLA) (Joe Garrido 2016, personal communication).

Time-series data from the three salinity-profiling wells in the basin were analyzed to gain insights into the timing, rates, and magnitudes of changes in lens thickness in response to seasonal, inter-annual, and episodic (storm) variations in rainfall (Figure 1.3.). Findings support the development of effective sustainable management practices, including

appropriate policy and management responses to storms and droughts. Improved understanding of observed lens dynamics will also help to improve the reliability of groundwater models.



Figure 1.2. NGLA Basins.



Figure 1.3. Observation wells in Yigo-Tumon Basin (www.guamhydrologicsurvey.com).

The quantity of groundwater available for extraction can be measured in terms of the freshwater lens thickness. Lens thickness can be measured directly from well salinity profiles and inferred indirectly from water levels. The lens thins or thickens in response to storage changes, changes in recharge and water withdrawal (production). The amount of recharge that replenishes the aquifer depends primarily on seasonal and inter-annual changes in rainfall. Major storms account for only a few percent of total rainfall but induce rapid responses in water levels and can thus have important immediate short-term effects on water quality. The timing and amounts of wet and dry season rainfalls are strongly influenced by El Niño Southern Oscillation (ENSO) events. Annual rainfall on Guam is reduced by as much as 50% during the year following strong El Niño (Lander 2016, personal communication). A strong El Niño is typically accompanied by a severe Micronesia wide drought, and typically results in some depletion of the freshwater lens, but the rate and magnitude of depletion has yet to be rigorously evaluated.

Lens thickness depends on the porous media properties, recharge, and discharge. Taborosi (2004) provides an inventory and describes characteristics of the karst terrains on Guam. Ayers (1995) and Rotzoll et al. (2012) applied the Ferris-Jacob equation to tide data and well-level records, determining regional hydraulic conductivity in the NGLA. Several research works have been done to estimate recharge that reaches the lens (c.f., Ayers 1995, Jocson et al. 2001, Habana et al. 2009, and Johnson 2013), and have estimated recharge to vary from about 40-67% of rainfall. Gingerich (2013) constructed a 3-D SUTra (Saturated Unsaturated Transport) steady-state model of the NGLA, using Johnson's (2013) recharge estimates.

This project builds on three significant WERI technical reports. Technical Report 141 (Bendixson et al. 2013) provides a comprehensive well and borehole database that was used to help acquire, organize and refine the data needed for this study. Technical Report 142 (Vann et al. 2014) describes the NGLA basement topography. This information provides subsurface geology as boundary conditions, setting, and basin divides. It also defines the spatial scope of this study in determining the boundaries of the Yigo-Tumon Basin. Simard et al. (2015) at the end of Technical Report 143, touched on the aquifer lens profile. Three cross-sections of the aquifer were drawn using borehole records and basement topography. Although their study of chloride and production does not locate the saltwater interface and its dynamics, their introduction into that topic provides the starting point for the hydrogeologic study of lens thickness, as defined by salinity profiles, which is the basis for this study.

1.1. Goals, Purpose, and Steps

The goal of this project is to characterize the response of the lens to natural, decadalscale climate variations. The ultimate purpose (application) of the results will be to provide an empirical basis for determining appropriate sustainable management practices, given the hydrogeologic complexity of the aquifer and the natural environmental stresses on it. This project consisted of the following steps:

1. Collect, examine, and organize available and useful historical meteorological data from National Climatic Data Center (NCDC) and groundwater data (USGS) from deep observation wells (DOWs) in the Yigo-Tumon Basin.

- 2. Apply hydrographic and statistical analyses for deep wells in the Yigo-Tumon Basin (EX-7, GHURA-Dededo (GD), and EX-10)(Figure 1.3.) and use applicable data (e.g., water level and transition zone response, and head-to-saltwater-interface ratios) to characterize saltwater profiles in each well.
- **3**. Interpret the analyses to determine the timing of changes in the lens thickness and how they relate to seasonal, inter-annual, and episodic changes in rainfall.
- 4. Infer what the responses to changes in rainfall may tell us about how to determine appropriate sustainable development strategies for the NGLA.

1.2. Scope, Limitations, and Delimitations

Scope: The geographical scope of this project is the Yigo-Tumon Basin (Figure 1.3.). The temporal scope is from 1982 to 2016 for water level and 2000 to 2016 for salinity profiles. Three DOWs are installed in the basin: EX-7, GD, and EX-10. These wells provide data from 2000 to the present on lens thickness along calculated flow lines. Data from 2000 to 2016 were analyzed for this study.

Limitations: DOW data provide a time series of water levels and salinity profiles for each well. These wells provide dynamic information on lens thickness. Long-term sea-level signals affect water table elevation, but not lens thickness. In separate, water-level monitoring wells (M-10A, M-11 and MW-2, Figure 1.3.), US Geological Survey (USGS) logs dynamic hydraulic head but does not measure the saltwater transition. Water levels from these wells can be used to infer a probable saltwater depth using the Ghyben-Herzberg ratio (40:1) (Fetter 2000).

Delimitations: This project is limited to the well set in the Yigo-Tumon Basin and available meteoric, tidal and climate data. Main variables of interest are water level, freshwater lens thickness, transition zone thickness, and seasonal lens thickness dynamics (time lag and response to recharge).

Chapter 2

BACKGROUND AND RELATED RESEARCH

The limestone in the northern half of Guam stores groundwater in the form of a freshwater lens and comprises the Northern Guam Lens Aquifer (NGLA). The NGLA's freshwater lens forms from infiltrated rain (recharge) buoyant on saltwater, diffusing at the freshwater-saltwater interface, which can be observed in deep observation wells (DOWs) and coastal caves. DOW salinity profiles reveal freshwater lens and saltwater transition zone dynamics, which reflect responses to recharge and sea level. The thickness of the freshwater lens as measured in EX-7, GHURA-Dededo (GD), and EX-10, ranges between 90-140 ft (27-43 m), and the transition zone thickness ranges between 40-120 ft (12-37 m) for all three wells.

Lens dynamics, position and thickness, may be influenced by sea level and groundwater recharge. Sea level and recharge can be influenced by natural climate cycles (e.g., El Niño, La Niña) that bring on unusual periods of prolonged low sea levels, drought, and irregular storm patterns in the region. Typhoons and storms may bring intense rainfall, which can infiltrate into effective recharge that thickens the lens. In contrast droughts can stop aquifer recharge while the lens continues to discharge, leading to a negative change in freshwater storage, thus thinning the lens.

Simard et al. (2015), *Salinity in the NGLA*, depicted lens thickness with cross-section figures of the aquifer using borehole data (Bendixson 2013), basement topography interpolation (Vann et al. 2014), and observation well data. This research advances from Simard's work, expanding on the lens profile by analyzing freshwater lens dynamics, including influence of climate variations and aquifer geology.

Observation well data have been collected by USGS and the Water and Environmental Research Institute of the Western Pacific (WERI) since 2000 when the wells were rehabilitated and the USGS/WERI collaboration started. This research refines the definition of freshwater lens and the transition zone and applies a time-series analysis using data from the observation wells in the Yigo-Tumon Basin. Analyses compare well data to ENSO index, rainfall, and sea level data to characterize lens response. Results may also provide insights into the aquifer's geologic structure and its hydrogeology. This chapter summarizes related literature, aquifer geology and hydrogeology, and data sources and quality.

2.1. Related Literature

The formation of a freshwater lens atop saline groundwater occurs in unconfined coastal and island aquifers. While the Ghyben-Herzberg (1889-1990) ratio of 40 to 1 (interface depth from mean sea level to hydraulic head) is the rule of thumb for lens aquifers, the approximation does not hold in all field cases. Literatures on the NGLA provide cross-section schematic diagrams, depicting the groundwater as a freshwater lens atop saltwater (c.f., CDM 1981, Jocson et al. 1998, Mylroie et al. 2000), however, such depictions usually have parts that are vertically exaggerated to make spatial relationships more visible. The freshwater-saltwater interface, for example, has been recognized as a halocline based on observation well salinity profiles, where chloride concentration increases with depth from fresh to saltwater, over a few feet to tens of feet.

Observation well water-level data have been used in earlier studies. Jocson et al. (1998) used the SWIG-2D numerical model to study recharge, well-level response, and examined storm recharge in observation wells M-10A and M-11. McDonald (2001) compared salinity patterns in production wells with salinity data from nearby observation wells in her study of the relation between well characteristics and salinity. Wuerch et al. (2007) applied a Fourier transform numerical analysis to match tide and observation well water-level response (EX-7, GD, EX-10). Habana et al. (2009) developed a recharge synthesis dynamic model into a finite element groundwater model to match water-level simulation to observation wells. Eeman et al. (2010) studied freshwater lens formation and transition zone response to recharge using analytical and numerical steady-state models for lens development. Their model results show a sharpening of the transition zone during recharge and lens thickening. Gingerich (2013) applied USGS' Saturated Unsaturated Transport, Graphical User Interface, (SUTra GUI), to create a 3-D model of the NGLA, using observation well salinity profiles to calibrate his model. In all efforts to model the NGLA, each recommended strategic placement of more observation wells to further improve modeling reliability and have a data-based understanding of lens thickness dynamics.

Simard et al. (2015) extended McDonald's 2001 study of salinity from production well data in the NGLA which was used to support Gingerich's model. Simard's study utilized DOW data and compared salinity profile depths to the depths estimated from the Ghyben-Herzberg rule (40:1) and showed that actual depths varied from 28:1 to 46:1. She defined the component layers of the phreatic zone in terms of the *prime layer* (freshwater) which extends from the water table to the depth at which salinity reaches 250 mg/L Cl⁻.

2.2. Geology

The geology of Guam (Tracey et al. 1964; Siegrist and Reagan, 2007) is the starting point for determining where groundwater and surface water may exist. Topography and geology determine the form and shape of watersheds and aquifer basin boundaries. Guam is made up of two major groups of rocks, divided by the Pago-Adelup fault into two distinct physiographic terrains, volcanic rocks in the south and a limestone plateau atop volcanic basement in the north (Figure 2.1). The Alutom Formation in the south continues through the Pago-Adelup Fault, beneath the NGLA, and crops out at Mt. Santa Rosa and Mataguac Hill.

The NGLA is composed of limestone deposits that began about 16 mya (Miocene-Pliocene) on top of Alutom terrain, in a reefal setting that has been uplifted to form the limestone plateau seen today. Two main limestone units, the Barrigada Limestone and the Mariana Limestone, comprise the aquifer.

Barrigada Limestone is a white, medium-to-coarse grained detrital limestone that was deposited in relatively deep waters in the Mio-Pliocene (Siegrist and Randall 1992, in Mink and Vacher 2004) by foraminifera along the volcanic flanks of the Alutom volcano. The Mariana Limestone was deposited in the Pliocene and Pleistocene under atoll-like conditions as evidenced by the presence of fore-reef facies, reef facies, detrital faces and molluscan facies (Tracey et al. 1964). Argillaceous limestone is formed adjacent to the Alutom Formation which extends across the fault and beneath the NGLA.



Figure 2.1. Geologic map of Guam (Siegrist and Reagan, 2007). The northern half of Guam is the NGLA, north of the Pago-Adelup fault, made up of 3 major limestone formations – Barrigada Limestone, Mariana Limestone, and the Argillaceous Member of the Mariana Limestone. South of the fault are volcanic formations of Facpi, Alutom, and Umatac. The Alutom Formation continues beneath the NGLA as the basement, seen cropping out at Mataguac Hill and Mt. Santa Rosa.

2.3. Northern Guam Lens Aquifer (NGLA)

The definition of an aquifer requires that a body of natural porous material must be able to capture, store, and release water in economically significant quantities. The US Environmental Protection Agency (USEPA) (1978) designated the NGLA as the primary source of utility water on Guam, supplying up to 90% of the island's municipal water. The NGLA is composed of young, eogenetic karst. The aquifer consists of highly permeable limestone bedrock underlain by much less porous volcanic basement rock (Figure 2.2). At the surface, limestone permeability is highest resulting in a lack of surface streams in northern Guam (Mink and Vacher 2004). While there are some limestone units in the south that store water, their productivity and quality for municipal use is considered much less



Figure 2.2. Schematic diagram of the NGLA.

favorable and less available compared to the NGLA (more than 100 production wells). Only three groundwater resource sites are in use in the south today – two vertical wells in Malojloj and a spring reservoir at Santa Rita. Most of the water in the south is surface water from Fena Reservoir and the Ugum Watershed.

The NGLA is an unconfined carbonate island karst aquifer (Mylroie and Jenson 2000). The aquifer has three laterally distributed freshwater zones: basal, parabasal, and suprabasal. In cross-section view (Figure 2.2.), the basal zone includes the freshwater underlain with saltwater. The parabasal zone is the area between the saltwater toe and mean sea level (msl). The suprabasal zone is the freshwater that occurs above msl over the basement.

The aquifer has undergone karstification, and most of the intense precipitation that falls in the north drains directly and quickly into the ground through sinkholes. Jocson et. al. (2002) found that during wet conditions, water levels can rise within hours, which suggested quick transmission into the aquifer during intense storms.

Vertically, the aquifer is divided into a vadose zone and a phreatic zone. The vadose zone is an important medium of recharge. Jocson et al. (2002) suggested that the thickness and saturation of the vadose zone influences how fast meteoric water gets to the lens. Water can take two paths down to the lens as is the nature of karstic aquifers. It can flow down through fast flow conduits during heavy storms (taking only a few hours), while water from more gentle rainfall can percolate through the matrix pores of the vadose zone which can take months to years (Lander 2001).

The phreatic zone is the zone of interest in this project, as it contains the freshwater lens, a freshwater-saltwater transition zone, and the underlying saltwater zone. The freshwater lens is an irregular lenticular freshwater layer floating on top of the denser saltwater base (Figure 2.2.). Freshwater from the lens discharges at the coast.

The freshwater lens of the NGLA is thought to be generally 120-150 ft (36-45 m) thick in its thickest parts. Between the freshwater and saltwater is a halocline, or transition zone, in which the concentration of saltwater increases with depth. The depth and thickness of this transition zone changes as the lens thins or thickens.

2.3.1. Hydrogeology and hydrology

Mylroie and Jenson (2000) describe the hydrogeology of small islands with volcanic basements overlain by young, diagenetically immature limestone. This aquifer has retained much of its original matrix porosity and developed secondary and tertiary features associated

with older, diagenetically mature aquifers. Dissolutional enhancement of fractures and conduits create a horizontal network of pathways for water to flow through. This results in a complex aquifer with hydraulic conductivities that vary widely on both local and regional scales. Island karst aquifers can be classed into types described by the Carbonate Island Karst Model (CIKM) (Jenson et al. 2006). The NGLA is composed of all the carbonate island karst model types: simple, carbonate-cover, composite, and complex. Basement topography (Vann et al. 2014) reveals locations of all the types of the CIKM model in the NGLA.

The Barrigada Limestone is the core of the aquifer in that it stores most of the available freshwater. In general, the Mariana Limestone occupies a peripheral barrier which is intersected by fractures, conduits, and flank margin caves, from which freshwater stored in the Barrigada Limestone discharges (Rotzoll et al. 2013). The Argillaceous Member of the Mariana Limestone in the south of the NGLA (in the Hagåtña Basin), has reduced permeability and hydraulic conductivity, resulting in the formation of small surface streams.

The porosity of the limestone units can vary locally from 10 to 25% (Mink and Vacher 1997). The porosity determines the hydraulic conductivity of the NGLA and influences water transmission into and discharge out of the aquifer. This hydraulic response is important for understanding how local and regional climate events affect lens thickness. Sinkholes, fractures, and large pore openings in the limestone bedrock facilitate fast recharge routes to the lens, while the small pores of the matrix provide the medium for percolating flow.

Rainfall on the NGLA infiltrates the surface and percolates through the deep limestone vadose zone (200-600 ft). When rain hits the surface, some of the rainfall is lost to evapotranspiration and some infiltrates to recharge (Jocson et al. 2002). Jocson et al. estimated 67% of annual rainfall on Guam is delivered to the lens, and the rest returns to the atmosphere through evapotranspiration. However, Johnson (2012), suggests that recharge is generally to 40-60%. When the infiltration rate is exceeded, surface runoff forms, streaming to surface-depression low points, ponding basins and sinkholes.

2.3.2. Freshwater lens dynamics

Lens dynamics in the NGLA are driven by meteoric recharge, discharge, and sealevel. Simard et al. (2015), however, observed that not all wells in the NGLA are equally influenced by these factors.

Recharge is dependent on rain infiltration, which is enhanced during high intensity rain and long periods of rainfall. This type of weather is expected during Guam's wet season, monsoon conditions, and typhoons. Observation well data have shown response to rainfall, especially under periods of stormy weather, similar to that observed in surface water hydrographs (c.f. Jocson et al. 2001, Habana et al. 2009). The dry season and prolonged droughts have much less rainfall, thus much less recharge. Partin et al. (2012) concluded that of the 30% of annual rainfall that falls during the dry season, none of it goes into the lens as recharge. In these periods, discharge exceeds recharge, thus a decrease in storage and thinning of the lens is expected.

Tidal signals and sea level may displace lens position. The buoyant freshwater rides on the vertical displacement of saltwater beneath as the sea level changes. The displacement attenuates inland and depends on hydraulic conductivity and frequency of the tidal/sea level signal. Tidal-signal and water-level relationships have been observed in some observation well data. Ayers et al. (1985) and Rotzoll et al. (2012) used tide and observation well data to estimate regional hydraulic conductivity. Olsen (2007) suggests El Niño can cause longer changes in sea levels as the result of changing winds and currents and that these changes have a significant effect on aquifer dynamics (Figure 2.3).

2.3.3. Climatology and sea level

Guam has a warm, wet/dry, tropical climate. It has characteristic wet and dry seasons with the wet season being July-November and the dry season December-June. Annual rainfall on Guam is 90-110 in (230-280 cm) and approximately two-thirds occurs from July to mid-November (Tracey et al. 1964). Tides are semidiurnal and have a mean range of 1.5 ft (0.5 m) with a diurnal range of up to 2.3 ft (0.7 m). Tidal/sea level changes do not affect freshwater lens thickness, only the vertical position of the lens within the aquifer.



Figure 2.3. Lens dynamics conceptual model.

Sea level and precipitation are affected during El Niño years with sea level dropping a foot or more and a shifting of precipitation patterns from wet to dry (Figure 2.4.). Guam tends to see El Niño about every 2-7 years, with a strong El Niño every 15-20 years. The effects of El Niño on lens thickness therefore need to be examined.



Figure 2.4. Timing of climatic hazards on Guam, associated with El Niño. El Niño events can have significant effect on lens dynamics. Heavy rain from tropical storm activity increases lens thickness, and prolonged drought in the Post-Peak Phase can thin the lens. Sea level drop can affect lens position within the aquifer (Lander, PEAC report).

2.3.4. Aquifer basin management

The NGLA is currently divided into 6 basins (Figures 1.2. and 2.5.). The Northern Guam Lens Study (CDM 1982) first delineated aquifer basins and zones for management. Vann (2014) redefined the basement divides that delineate the basins. Flowline boundaries are based on Gingerich (2013). Shalilian (2017) recommended the re-delineation between the Finegayan and Yigo-Tumon basins, with consideration of the hydrogeologic divide along the Pugua Fault.

2.4. Yigo-Tumon Basin Related Data

The scope of this project is the analysis of lens dynamics observed in the three observation wells in the Yigo-Tumon Basin. Observation well data from Guam are managed and collected by the USGS Pacific Island Water Science Center and WERI, funded in cooperation through the Comprehensive Water Monitoring Program (CWMP) and National Streamflow and Groundwater Information Program. Of the 15 observation wells managed through the CWMP, five are in the Yigo-Tumon Basin (Figure 1.3.). Rainfall and Oceanic Niño Index (ONI) are from the National Climate Data Center (NCDC, part of NOAA) available in their website database (see Chapter 3 for data sources), respectively. The following subsections cover data types, sources, and level of quality for the observation wells.

2.4.1. Observation wells

Wells on Guam are either production wells or observation wells (Bendixson et al. 2013). Some observation wells monitor only water levels, such as M-10A and M-11, while others fully penetrate the lens to saltwater (EX-7, GD, EX-10) (Figures 1.3. and 2.6.). The focus of this study is the observation wells in the Yigo-Tumon basin, specifically EX-7, GD, and EX-10.

Water level is measured quarterly in all wells, and continuously in EX-7 and EX-10. Quarterly measurements are taken using a steel tape or e-tape. Continuous water levels are measured using vented transducer/loggers. Specific conductance profiles are collected quarterly, using conductivity-temperature-depth (CTD) loggers. The data are downloaded from the loggers and are processed (quality screening) and verified by USGS standards (see Table 3.1. Data Sources).



Figure 2.5. NGLA basin delineation. Basal delineation over the basal zone based on groundwater model water table flowlines.



Figure 2.6. Schematic diagram of observation wells in the NGLA. Deep observation wells (far left) penetrate the entire lens. Others (middle and right) monitor only water levels.

Chapter 3

METHODS

One of the objectives of this project was to apply graphical time-series and basic statistical analyses to the collected and organized data from observation wells and contributing hydrologic variables. This chapter will cover the methods for each data analysis. The data used in the analyses are available online and are discussed and access-referenced in the first section of this chapter (Table 3.1).

3.1. Data Sources

Observation well and climate data are readily available from online sources (Table 3.1). The observation well data used are from the CWMP, Guam P.L. 24-161, which contracts the USGS' Pacific Islands Water Science Center to collect and post Guam's observation well data on their website. The Guam Hydrologic Survey (GHS) (Guam P.L. 24-247) website organizes these USGS data links and borehole information in the NGLA Borehole Database. Rainfall data are available for Guam in the archives of the NCDC and USGS, websites with links accessible in the Guam Hydrologic Survey (GHS) and may be obtained from the NCDC online by request via e-mail. Oceanic Niño Index (ONI) data are available in National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center (1950-2018). ONI is used to determine El Niño conditions in the east-central tropical Pacific region (120°-170°W). Sea level data are measured from the NOAA gage in Apra Harbor. For this study, data spanning 2000-2016 were gathered and organized. Table 3.1. organizes the data and online references.

Observation	URL link
EV 7	http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_n
EA-7	<u>o=133119144491771</u>
EY_10	http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_n
	<u>o=133224144495271</u>
GHURA-	http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_n
Dededo	<u>o=133120144505471</u>
NA 10A	http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_n
IVI-IUA	<u>o=133032144491871</u>
NA 11	http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_n
	<u>o=133047144500171</u>
Dainfall	https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd?datasetabbv=GSOD
Kallilali	&resolution=40
	http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.sht
ONI	<u>ml</u>
Sea level	https://www.ngdc.noaa.gov
SST	https://www.ngdc.noaa.gov

Table 3.1. Data Sources

3.2. Data Analysis

Four analyses were undertaken for each of the three deep observation wells: 1) salinity profiling; 2) salinity time series and basic statistics; 3) multivariate correlated times series; and 4) salinity boundary frequency analysis. For each, a Microsoft Excel® spreadsheet was used for organizing tables and preparing graphs. Salinity profiles were graphed and examined for determining and defining the phreatic interfaces and transition zones. A multi-variable time-series analysis was made for each well to correlate contributing hydrologic variable data of ONI (ENSO), sea level, and rainfall to the phreatic graphs. Finally, for each deep observation well, a vertical graph of frequency analysis of the phreatic interfaces (defined in the next section) was done. Each of these analyses is described below.

3.2.1. Using salinity profiles to define phreatic zone anatomy

Several salinity profiles from EX-7, GHURA-Dededo (GD), and EX-10, were graphed and examined for patterns and characteristic shapes (Figure 3.1.). The USEPA secondary standard for freshwater (250 mg/L Cl⁻/1100 μ S/cm) was used as the definition of freshwater (which Simard et al. 2015 called the *prime layer*) for this study. The transition zone was sub-divided into brackish, saline, and saltwater based on definitions from *The Glossary of Hydrology* (Wilson and Moore 1998).



μS/cm

Figure 3.1. Salinity profile for defining phreatic zone anatomy. The shape of the graph is common to the observation wells in Yigo-Tumon Basin.

This study defines the top of the freshwater lens as the water table and the bottom of freshwater lens (BoFL) as the level at which conductivity reaches $1100 \,\mu$ S/cm. The

freshwater grades sharply at the beginning of the transition zone consisting of brackish and saline water and ending in saltwater at the BoTZ (bottom of transition zone, >49000 μ S/cm). Figure 3.1. defines phreatic zone anatomy and shows the three interfaces of interest: 1) the freshwater/brackish interface; 2) the brackish/saline interface; and 3) the saline/saltwater interface. The establishment of phreatic profile definitions determines the selected data for extraction from each quarterly measured salinity profile. These data are then used for the time-series and statistical analyses of the phreatic zones for each well.

3.2.2. Time-series analysis of observation well data

With phreatic zone anatomy defined, time series of interface-depth graphs can be generated for each of the DOWs (EX-7, GD, and EX-10). Freshwater-brackish interface (BoFL), brackish-saline interface (50% chloride), and saline-saltwater interface (BoTZ) data were extracted and graphed, spanning 16 years, 2000-2016.

Freshwater lens thickness can be calculated from the difference between water-level elevation and the depth to the BoFL. The transition zone thickness is the difference between BoFL and BoTZ. The time-series graphs are available in the results section. Statistical analysis was done for each interface, lens thickness, and transition zone thickness. Minimum, maximum and averages were calculated for these components. Minimum and maximum and percent changes from average were also determined and shown. The Ghyben-Herzberg ratio was used as a guide to calculate actual head-to-saltwater-interface ratios from water-level data for all DOWs. This ratio was averaged between the three wells and then applied to M-10A and M-11. This was done to estimate 50% isochlor depth.

3.2.3. Development of a multi-variable time-series analysis

A multi-variable time-series analysis was developed that compares contributing hydrologic variables to observation well time-series data. It is basically an observation well hydrograph of phreatic zone interfaces with time-aligned graphs of climactic factors: ONI (ENSO) index, sea level and rainfall. As mentioned in the previous chapter, observation well response may be a result of meteoric recharge, sea level changes, and ENSO effects on sea level and rainfall in the region. The prepared graphs for ONI, sea level, and rainfall are aligned above charts of observation well water-level, salinity transition zone, and interfaces. This analysis will elucidate the major effects of influential elements on the lens.

Strong El Niño and La Niña events are observed to affect Guam's climate. The Oceanic Niño Index (ONI) defines El Niño and La Niña events. Three-month running averages of ONI and SST (Sea Surface Temperature), 2000-2016, are charted and placed at the top. Graphs of daily rainfall and 5-year running sum of rainfall are placed below the ENSO index chart, and below that, the daily average sea level data. The data from the observation wells (well level, transition zone interfaces, and lens thickness) are graphed beneath climactic variables. The multi-variable time-series analysis charts of EX-7, GD, and EX-10 are in the Results section.

3.2.4. Development of a frequency analysis of phreatic zone interfaces

Finally, a vertical frequency analysis of observation well interfaces was developed for each DOW in the Yigo-Tumon basin. A Microsoft Excel® histogram analysis was done for each interface (with the exception of the brackish-saline interface), water level and transition zone, and is displayed in the Results.

Chapter 4

RESULTS

The graphs in this section are the results of techniques described in Chapter 3. These results are shown in time-series graphs that correlate the selected contributing hydrologic variables to the vertical displacement of the phreatic interfaces. The contributing variables examined are ONI, SST (Figure 4.1.), sea level (Figure 4.2.), and rainfall (Figure 4.3). Long term correlations of water level and rainfall for EX-7 are shown in Figure 4.4. Daily water levels in each well are graphed in Figure 4.5. The contributing hydrologic variables and phreatic interfaces time-series are then correlated in a multi-variable phreatic-interface hydrograph (Figures 4.6-4.8). Figure 4.9. shows calculated depth to the 50% isochlor for two water level only wells. Figure 4.10. shows the correlative time-series of climate variables and hydrographs for each well. Finally, Figure 4.11. shows phreatic-interface elevation-frequency-distribution histograms and basic statistical analyses for each deep observation well (DOW) in the Yigo-Tumon Basin.

4.1. Contributing Hydrologic Variables

As mentioned in Chapter 2, NGLA lens dynamics is influenced by external hydrologic variables, most especially rainfall and sea level fluctuations. This section displays observed correlations between phreatic-interface levels and rainfall and sea level. It should be noted that to interpret the correlations of groundwater levels with changes in rainfall, one must remove the sea-level signal from the water-level signal.

4.1.1. ONI, ENSO, and sea level

The Oceanic Niño Index (ONI) (Figure 4.1.) indicates where Guam's climate is in the El Niño Southern Oscillation (ENSO) climate pattern. ONI provides a record of the occurrence of El Niño and La Niña conditions for Guam. El Niño is declared when the ONI index is +0.5 or higher. Strong El Niño is defined when the ONI is +1.5 or higher. In the period of record for this study, there are four El Niño occurrences and one strong El Niño event.

Sea level (Figure 4.2.) is also influenced by ENSO. Long-term (ie. low frequency) sea level fluctuations extend inland and influence lens position. During El Niño years, sea level can drop by as much as 0.5 ft below mean sea level (bmsl).

4.1.2. Rainfall

Guam's average annual rainfall is 100 in. Recharge into the NGLA is from rainfall infiltration, which results in lens thickening. Figure 4.3 displays a) daily, b) monthly, and c) annual rainfall records. The daily graph also includes the 5-year running sum of rainfall. The peak of the running sum marks the end of the second wettest 5-year period on record (2000-2004), and the low point of this line marks the end of the second driest 5-year period on record (2005-2009). The year 2004 is noted for a wetter-than-average wet-season. On June 27, 2004, Typhoon Ting-Ting set the all-time record of single-event rainfall with over 20 in within 24 hours (Lander 2017, personal communications). June and August of 2004 each had more than 40 in of rain (Figure 4.3b). In 2005 through 2009, there were no24-hour rainfalls greater than five inches, referred to here as "The Big Nothing".



Figure 4.1. ONI and SST, 2000-2016. The bars represent the 3-month moving average of the ONI record. Yellow is index above 0.5 (El Niño), red is index greater than 1.5 (Strong El Niño), gray bars (negative index) are La Niña (less than -0.5). SST history is represented in the line graph, degrees Celsius.



Figure 4.3(c) shows annual rainfall. The dark blue bars are greater than 120 in, indicating a wetter than average year (100 in). The green bars are years with less than average rainfall but greater than 80 in. 2016 had less than 80 in and is considered a drought year, indicated in yellow.



Figure 4.3. Rainfall record, 2000-2016 (NCDC). Top chart (a) is daily rainfall, middle (b) is monthly total, and bottom (c) is annual rainfall.

4.1.3. Correlation between rainfall and well water-levels

The correlation between rainfall and water-level elevation was important for determining the communicative relationship between them. To determine the correlation, daily water-level elevation for EX-7 was graphed along with rainfall for the same time period. Rainfall data were an annual running sum of daily rainfall (in). Sea level effects on vertical lens displacement were removed (Figure 4.4).



Figure 4.4. Correlation of rainfall with well water-levels at EX-7. This graph shows that daily well water-level is closely correlated with rainfall.

4.2. Well Levels and Freshwater-Saltwater Transition Zone

This section reports graphical analysis of lens dynamics for each deep well, specifically changes in well level and freshwater-saltwater transition zone thickness in response to rainfall and sea level.

Two types of water-level analyses were done: The first analysis used daily water levels (1982-2016) in all 5 wells (EX-7, GHURA-Dededo (GD), EX-10, M-10A, and M-11, Figure 1.3.) to examine water-level response to rainfall. The second analysis used quarterly water-level data in the 3 deep wells (EX-7, GD, and EX-10, Figure 1.3.), from 2000-2016, for lens-thickness analysis.

4.2.1. Well levels

Water-level data go back to 1982. Figure 4.5. shows each daily water-level record for EX-7, GD, EX-10, M-10A, and M-11, in the Yigo-Tumon Basin as a line graph. The top chart is water-level graphs spanning from 1982 to early 2016. The bottom chart, 2004-2016, was prepared in order to show refinement of the data collection techniques using upgraded and more reliably calibrated level loggers (Presley 2016, personal communication).

Four of the wells, M-10A, EX-7, EX-10 and GD, display similar behaviors. M-11, however, shows a much greater responsiveness to recharge than the other wells.

4.2.2. Lens dynamics (to scale)

Lens dynamics for the three DOWs in the Yigo-Tumon Basin were graphed using quarterly specific conductance profiles over 16 years. This section describes the results of graphical and statistical analyses of wells EX-7, GD, and EX-10.



Figure 4.5. Daily water levels in the Yigo-Tumon Basin. Top chart records from 1982-2016 and bottom chart 2004-2016. Bottom chart was made to show, in a wider-spread display, data from refinement in well level measurement techniques specifically using upgraded and more reliably calibrated level loggers, most notably at M-10A and EX-7, starting in 2004.

4.2.2.1. EX-7

Data extracted from the quarterly profiles are water level (top of the freshwater lens), 1100 μ S/cm (bottom of the freshwater lens (BoFL)/top of the brackish zone), 25000 μ S/cm (top of the saline zone), and 49000 μ S/cm (bottom of the transition zone (BoTZ)/top of the saltwater zone) (Figure 3.1). These parameters are graphed in a time-series for EX-7 in Figure 4.6. The turquoise line at the very top shows the water level. The blue line that starts at about –100 ft shows the elevation below mean sea level (bmsl) of the BoFL. Groundwater above this line is below 250 mg/L Cl⁻ (1100 μ S/cm). This level also constitutes the beginning of the transition zone (TZ). The green line that starts at about –120 ft, indicates the elevation (bmsl) of 25000 μ S/cm conductivity. Groundwater at this level is inferred to be 50% freshwater and 50% saltwater. While the 50% isochlor is frequently used to arbitrarily define the bottom of the freshwater lens, this study accounts for the transition zone and resolves it into a brackish (1100-25000 μ S/cm) zone and a saline (25000-49000 μ S/cm) zone.



Figure 4.6. EX-7, phreatic zone dynamics, 2000-2016. The groundwater between the blue line and the green line is designated as brackish and ranges from 250 mg/L Cl⁻ (1100 μ S/cm) to 8100 mg/L Cl⁻ (25000 μ S/cm). Groundwater between the green line and the red line is designated as saline and ranges from 8100 mg/L Cl⁻ (25000 μ S/cm) to 16000 mg/L Cl⁻ (49000 μ S/cm). The red line is the elevation bmsl of 49000 μ S/cm, which defines the bottom of the transition zone (BoTZ), below which is defined as saltwater (salinity equivalent to seawater).

The average elevation of the water level at EX-7 is 3.5 ft above mean sea level (amsl). The lowest water level was in 2001 when it measured 2.9 ft amsl, 16% lower than average. The highest water level occurred in 2015 when it measured 4.3 ft amsl, an increase of 22% (Table 4.1.).

The bottom of the freshwater lens (BoFL) in this well fluctuates up and down during this time series. The average depth of this level is 106.3 ft bmsl. The freshwater lens was shallowest in 2009 at 92.3 ft bmsl, 13% shallower than average. It was deepest in 2004 at 122.6 ft bmsl, a 15% increase in depth.

The 25000 μ S/cm interface shows little variation over time. The average depth of this level is 119.7 ft bmsl. This level was shallowest in 2010 at 113.5 ft bmsl, 5% shallower than average. It was deepest in 2004 at 128.7 ft bmsl, an 8% increase in depth.

The BoTZ is the lowest phreatic boundary and shows dramatic variation over this time series. The average depth of this level is 170.3 ft bmsl. This level was shallowest in 2001 at 146.9 ft bmsl, 14% shallower than average. It was deepest in 2004 at 216.3 ft bmsl, a 27% increase in depth.

The freshwater lens shows thickening and thinning during this time series. The average thickness is 109.8 ft. The lens was thinnest in 2009 at 95.9 ft, 13% thinner than average. It was thickest in 2004 at 126.2 ft, 15% thicker than average.

The transition zone (TZ) at EX-7 shows the greatest variability of any component during this time series. The average thickness of the TZ is 63.8 ft. The TZ was thinnest in 2007 at 45.6 ft, 28% thinner than average. It was thickest in 2004 at 101.5 ft, 59% thicker than average. Phreatic zone statistics are summarized in Table 4.1.

Components	Average	Date	Min	% Change (-) Date	Max	<mark>% C</mark> hange (+)
Water level (ft amsl)	3.5	9/7/2001	2.9	16%	7/11/2015	4.3	22%
1100 µS/cm (ft bmsl)	106.3	12/3/2009	92.3	13%	12/14/2004	122.6	15%
25000 μS/cm (ft bmsl)	119.7	6/9/2010	113.5	5%	12/14/2004	128.7	8%
49000 μS/cm (ft bmsl)	170.3	5/17/2001	146.9	14%	10/27/2004	216.3	27%
Lens thickness (ft)	109.8	12/3/2009	95.9	13%	12/14/2004	126.2	15%
TZ thickness (ft)	63.8	6/5/2007	45.6	28%	9/13/2004	101.5	59%

Table 4.1. EX–7 phreatic zone statistics

4.2.2.2. GHURA-Dededo

A time series of the phreatic zones at GD is shown in Figure 4.7. The average elevation of the water level at this well is 3.7 ft above mean sea level (amsl). The lowest water level occurred in 2007 when it measured 3.2 ft amsl, 15% lower than average. The highest was in 2015 when it measured 4.4 ft amsl, an increase of 20% (Table 4.2.).



2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 Figure 4.7. GD, phreatic zone dynamics, 2000-2016.

Like EX-7, the bottom of the freshwater lens (BoFL) in this well fluctuates substantially up and down during this time-series. The average depth of this level is 121.1 ft bmsl. The BoFL was shallowest in 2009 at 111.2 ft bmsl, 8% shallower than average. It was deepest in 2005 at 139.6 ft bmsl, a 15% increase in depth.

The 25000 μ S/cm level shows little variation during this time of record. The average depth of this level is 135.6 ft bmsl. This level was shallowest in 2011 at 125.6 ft bmsl, 7% shallower than average. It was deepest in 2004 at 152.0 ft bmsl, a 12% increase in depth.

The BoTZ shows the most variation over this time series. The average depth of this level is 152.5 ft bmsl. This level was shallowest in 2011 at 137.1 ft bmsl, 10% shallower than average. It was deepest in 2005 at 182.5 ft bmsl, a 20% increase in depth.

The freshwater lens shows substantial thickening and thinning during this time series. The average thickness is 124.6 ft. The lens was thinnest in 2009 at 114.6 ft, 8% thinner than average. It was thickest in 2005 at 143.2 ft, 15% thicker than average.

Similar to EX-7, the transition zone at GD shows the greatest variability of any component during this time series. The average thickness of the TZ is 31.4 ft. The TZ was thinnest in 2014 at 24.7 ft, 21% thinner than average. It was thickest in 2004 at 43.9 ft, 40% thicker than average. Phreatic zone statistics are summarized in Table 4.2.

Components	Average	Date	Min	% Change (-) Date	Max	% Change (+)
Water level (ft amsl)	3.7	3/14/2007	3.2	15%	7/11/2015	4.4	20%
BOFL: 1100 µS/cm (ft bmsl)	121.1	6/11/2009	111.2	8%	2/23/2005	139.6	15%
25000 μS/cm (ft bmsl)	135.6	7/15/2011	125.6	7%	12/16/2004	152.0	12%
ETZ: 49000 µS/cm (ft bmsl)	152.5	7/15/2011	137.1	10%	2/23/2005	182.5	20%
Lens thickness (ft)	124.6	6/11/2009	114.6	8%	2/23/2005	143.2	15%
TZ thickness (ft)	31.4	6/28/2014	24.7	21%	10/28/2004	43.9	40%

 Table 4.2. GD Phreatic zone statistics

4.2.2.3. EX-10

The time-series of the lens layers at EX-10 is shown in Figure 4.8. The average elevation of the water level at this well is 3.3 ft above mean sea level (amsl). The lowest water level occurred in 2007 when it measured 2.9 ft amsl, 12% lower than average. The highest was in 2004 when it measured 3.8 ft amsl, an increase of 18%.

The bottom of the freshwater lens (BoFL) in this well fluctuates gently up and down during this time series. The average depth of this level is 99.6 ft bmsl. This level was shallowest in 2001 at 92.2 ft bmsl, 7% shallower than average. It was deepest in 2005 at 108.1 ft bmsl, a 9% increase in depth.

The 25000 μ S/cm interface shows little variation during this time of record. The average depth of this level is 116.0 ft bmsl. This level was shallowest in 2012 at 109.9 ft bmsl, 5% shallower than average. It was deepest in 2006 at 124.5 ft bmsl, a 7% increase in depth.

The BoTZ also shows remarkably little variation over this time-series. The average depth of this level is 139.3 ft bmsl. This level was shallowest in 2001 at 132.8 ft bmsl, 5% shallower than average. It was deepest in 2003 at 144.1 ft bmsl, a 3% increase in depth.



Figure 4.8. EX-10, phreatic zone dynamics, 2000-2016.

The freshwater lens shows minor thickening and thinning during this time series. The average thickness is 102.8 ft. The lens was thinnest in 2001 at 95.3 ft, 7% thinner than average. It was thickest in 2005 at 111.6 ft 9% thicker than average.

The transition zone at EX-10 shows less variability than at EX-7 or GD. This well does not respond to recharge in the same way as EX-7 and GD. The average thickness of the TZ is 39.7 ft. The TZ was thinnest in 2005 at 35.5 ft, 11% thinner than average. It was thickest in 2004 at 47.2 ft, 19% thicker than average. Phreatic zone statistics are summarized in Table 4.3.

4.2.2.4. M-10A and M-11, Ghyben-Herzberg

Depths of the 25000 μ S/cm (saline/brackish) interfaces were assumed based on the Ghyben-Herzberg concept of 40:1. The ratios were empirically determined for EX-7, GD, and EX-10 and then averaged, resulting in 36:1. This ratio (36:1) was then applied to the water level data for water-level only wells, M-10A and M-11 to show where the saline/brackish interface might be based on the DOWs in the Yigo-Tumon Basin. The resulting calculated depths are shown in Figure 4.

Components	Average	Date	Min	% Change (-) Date	Max	<mark>% C</mark> hange (+)
Water level (ft amsl)	3.3	3/14/2007	2.9	12%	6/22/2004	3.8	18%
1100 μS/cm (ft bmsl)	99.6	5/17/2001	92.2	7%	8/29/2005	108.1	9%
25000 μS/cm (ft bmsl)	116.0	1/12/2012	109.9	5%	5/11/2006	124.5	7%
49000 μS/cm (ft bmsl)	139.3	5/17/2001	132.8	5%	8/1/2003	144.1	3%
Lens thickness (ft)	102.8	5/17/2001	95.3	7%	8/29/2005	111.6	9%
TZ thickness (ft)	39.7	8/9/2005	35.5	11%	2/26/2004	47.2	19%

Table 4.3. EX-10 phreatic zone statistics



Figure 4.9. Calculated depth of 25000 μ S/cm level for M-10A and M-11 using a 36:1 ratio derived from the three deep wells.

4.2.3. Lag time response

Lag time response of the freshwater lens refers to the time it takes for the lens to respond (thickening or thinning) to abundant recharge or drought conditions. During this 16-year time series, there is a period of above-average rainfall in June and August of 2004 (Figure 4.3.). During those two months alone, Guam saw a total of 80 inches of rainfall (80% of its average annual rainfall), including Typhoon Ting-Ting in June, which is the wettest storm on record. From 2005-2009, Guam experienced a drought where the average annual rainfall for this time period was below 100 inches (Figure 4.3.). For this study, thickening lag time response in months and thinning lag time response in years, was calculated post-August of 2004 to show lens response to abundant rainfall as well as drought condition response (Table 4.4).

4.3. Multi-graph Analysis

In Figure 4.10., the hydrographs of each well are compared with one another and with the climactic variables that are driving and/or correlating with them: ONI, rainfall, and sea level. The temporal major axes are labeled yearly, minor ticks-marks are 6 months, and the smallest time record is daily. Rainfall, average sea level, and water level are daily. A 5-yr running sum of rainfall is charted (orange line, secondary axis). ONI, as El Niño/La Niña

				Thinning			
	FW lens thickness, ft (6/22/2004)	FW lens thickness (thickest post-Aug 2004), ft	FW lens lens thickening I FW lens lag time (post-Aug (%Δ 2004), mo		FW lens thickness (thinnest post-Aug 2004), ft	FW lens %Δ	lens thinning lag time (post-Aug 2004), yr
EX-7	113	126	12%	6	96	-24%	5
GD	129	143	11%	8	115	-20%	4.3
EX-10	104	112	8%	14	97	-13%	4.3

Table 4.4. Lag response for EX-7, GHURA-Dededo, and EX-10

signal, is a three-month moving average, with color codes on the secondary axis: (0-0.5) black, (0.5-1.5) gold, (>1.5) red. The phreatic data for each DOW (EX-7, GD, EX-10) are water level (hydraulic head), transition zone boundaries, and lens thickness. Water level is either by daily logger, or periodic points with 1/yr to 7/yr intervals. Transition zone data include the Ghyben-Herzberg 40:1 computation to show estimated depth of $25000 \,\mu$ S/cm (yellow line in Figure 4.10. b, c, and d) as opposed to calculated depth based on quarterly water-level measurements (dotted black line in Figure 4.10. b, c, and d). Elevations are shown for hydraulic head and transition zone boundaries; units are in feet. Lens thickness is the difference between the measured hydraulic head and BoFL. Note that phreatic layering is inverted in each hydrograph.



4.4. Frequency Analysis of Phreatic Interfaces

Figure 4.11 shows three graphs with elevation (vertical axis, ft bmsl) and frequency distribution (horizontal axis) of the phreatic interfaces for water level, BoFL, and BoTZ. Other information includes Ghyben-Herzberg depths and basic borehole information for each well, including the nearest distance to shore. The next chapter is a discussion of the results DOWL EX-7: Lens dynamics histogram (2001 - 2016) DOWL EX-10: Lens dynamics histogram (2001 - 2016) DOWL EX-10: Lens dynamics histogram (2001 - 2016)



Figure 4.11. Frequency analysis of phreatic interface elevations. Horizontal axes are depth frequency, top axis for water level, and transition zone axis at -75 ft. The general range of production well depths (25 to 40 ft bmsl) is shown on each graph.

Chapter 5

DISCUSSION

Section 5.1., below, discusses the correlation of water levels in EX-7 with annually averaged rainfall over the period of record (2000-2016), as shown in Figure 4.4. Section 5.2. addresses the thickness history of the fresh, brackish, saline, and saltwater zones for each of the three wells (EX-7, GHURA-Dededo (GD), EX-10) from 2000-2016, as shown in Figures 4.6.-4.8.

Section 5.3. addresses observations from a comparative historical analysis of the correlation of phreatic interface elevations with the Oceanic El Niño Index, 5-year running sum of rainfall, and sea levels for 2000-2016, as shown in Figure 4.10.

Section 5.4. provides interpretations of the elevation-frequency distributions for the phreatic interface elevations for each of the three deep observation wells (DOWs), as shown in Figure 4.11.

5.1. Correlation Between Water Level and Annual Rainfall in EX-7

The close correlation between the annual (365-day) running total rainfall and the daily well-water-level curve shown in Figure 4.4. shows that the characteristic water-level time of response in EX-7 to seasonal rainfall is less than a year. The inter-annual trends are almost perfectly matched. These observations suggest that the recharge component of rainfall generally descends to the water table within a year of the rainfall event that deposited it and that the rate of recharge reflects an annual average of the seasonal distribution.

5.2. Groundwater Recharge and Freshwater Lens Response

Figures 4.6.-4.8 in Section 4.2.2, Lens Dynamics, show the phreatic interfaces for each well thickening and thinning over the 2000-2016 study period. Of the three phreatic interface graphs, EX-7 (Figure 4.6) shows the most extensive transition zone response. The transition zone of EX-7 is the thickest, and GD (Figure 4.7) is the thinnest. EX-7 has a thick saline layer, thickest in 2004, 100 ft, responding promptly to Typhoon Ting-Ting, which delivered more than 20 in of rainfall in 24 hours. Following that record storm, the brackish layer thinned in each of the three wells, apparently giving way to thickening of the freshwater layer above, the base of which descended in each well. EX-10 in general shows a more muted response than the other two wells, in this case showing longer lag and more gradual response in the thinning of the brackish zone. The EX-10 brackish zone thinning reached it thinnest after three years, while EX-7 and GD's brackish zone thinned to their minima before the end of the year. For each case, following the recharge from intense storms, the freshwater lens deepens, the brackish layer thins, and the saline layer thickens. Further analysis on transition zone dynamics will be needed to address such questions as why the saline zone thickens as the brackish zone thins.

In addition to the response to the 2004 storm, Figures 4.6-4.8 also show lens responses to interannual variations between abundant rainfall and drought. The 2000-2016 period of record fortuitously includes not only a record storm (Typhoon Ting-Ting) but the storm is bracketed by the second-wettest 5-year period (2000-2005) and the second-driest (2005-2009) 5-year period ever recorded. The wettest 5-year period in this time-series saw over 100 inches of rainfall annually, with 2004 having over 120 inches. (Average rainfall is

100 in, with a standard deviation of 22 in). In June and August of 2004, Guam received a combined 80 inches of rain (40 inches each month) which is 80% of the average annual rainfall. The driest 5-year period in this time-series followed, beginning in 2005 and is designated as "The Big Nothing" (Lander 2010, personal communication) in which annual rainfall was less than 100 inches (approximately 20% less than average) (Figure 4.3.).

Charting lens response to these climate events (Figure 4.10) provides insights into aquifer capacity for long-term storage. The lens response at each well can be seen before and after these periods of rainfall or drought. Lens thickness was measured pre-June 2004, and then again after August 2004, when the lens was at its thickest. The lag time was then calculated to determine response to abundant rainfall. For drought response, lens thickness was measured post-August 2004, and lag time to the thinnest measurement was determined (Table 4.4.). The graphs show that after 2005 into The Big Nothing, the thinning of the freshwater lens occurred at rates of 4-6 ft/yr for the three DOWs (Table 5.1.).

Table 5.1.	Freshwater	lens	thickening	and	thinning	rates
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	Thicken	Thin
EX-7	2.2 ft/mo (26 ft/yr)	0.5 ft/mo (6 ft/yr)
GD	1.8 ft/mo (22 ft/yr)	0.5 ft/mo (6 ft/yr)
EX-10	0.6 ft/mo(7 ft/yr)	0.3 ft/mo (4 ft/yr)

In the transition zone, during this period of drought, the saline zone is slowly thinning, while the brackish zone is thickening. The brackish-saline interface is the least dynamic interface. The following subsections are specific discussion for each DOW.

5.2.1. EX-7 phreatic interface dynamics

In June 2004, the freshwater lens at EX-7 was 113 ft thick, 3 ft thicker than average (110 ft) (Figures 4.6 and 4.10b). It reached its thickest, 126 ft, in December 2004 over a lag time of about six months, thickening at an average rate of 2.2 ft/mo. Post-August 2004, the lens at EX-7 was thinnest, 96 ft, in December 2009, thinning over lag time of five years at an average rate of 6.0 ft/yr (Table 4.4. and Table 5.1.). This suggests that recharge from the surface flows quickly to the lens during periods of high rainfall. Discharge from the lens, however, is slower.

5.2.2. GHURA-Dededo phreatic interface dynamics

In June 2004, the freshwater lens at GD was 129 ft thick, 4 ft thicker than the average thickness of 125 ft (Figures 4.7., 4.10c). It reached its thickest, 143 ft, in February 2005 showing a thickening lag time of eight months at an average rate of 1.8 ft/mo. Post-August 2004, the lens at GD was thinnest, 115 ft, in June 2009, resulting in a thinning lag time of 4.3 years at an average rate of 6 ft/yr (Table 4.4. and Table 5.1.). GD responds to rainfall similarly to EX-7 with recharge reaching the lens quickly and taking much longer to discharge and therefore thin. EX-7 and GD may be located in similar hydrogeologic conditions as they both lie along the axis of the Yigo Trough (Figure 1.3.) which might explain their similar thickening and thinning behaviors.

5.2.3. EX-10 phreatic interface dynamics

In June of 2004, at the time of the storm, the freshwater lens at EX-10 was 104 ft thick, very close to the average of 103 ft thick (Figures 4.8, 4.10d). It reached its thickest, 112 ft, in August 2005 showing a thickening lag time of 14 months at an average rate of 0.6 ft/mo. Post-August 2004, the lens at EX-10 was thinnest, 97 ft, in December 2009, thinning over 4.3 years at an average rate of 4 ft/yr (Table 4.4. and Table 5.1.). EX-10, which lies north of the axis of the Yigo-Tumon Trough, shows a different response to recharge than EX-7 and GD. It takes almost twice as long for the lens at EX-10 to thicken compared with the other two wells. Both EX-7 and GD, which lie along or near the axis of the Yigo Trough, respectively, thicken and thin at similar rates (around 2 ft/mo to thicken and 6 ft/yr to thin). EX-10 is located north of the axis of the Yigo Trough (Figure 1.3.) and has a much slower rate of thickening and thinning (0.6 ft/mo to thicken to maximum and 4 ft/yr to thin to minimum).

5.3. Multi-graph Comparison

Figure 4.10 displays the ENSO history, 5-year running rainfall total, and sea-level history for 2000-2016 with corresponding measured water levels and internal phreatic boundary levels for each of the three DOWs. The following subsections discuss observed relations between these climate variables and the lens dynamic behavior in each well.

5.3.1. Oceanic Niño Index

The ONI provides a record of the occurrence of El Niño (ENSO) conditions for Guam. Knowing where Guam is in the ENSO cycle is important to understand as this phenomenon dictates the amount of rainfall the island receives. During El Niño years, there is a pattern of initially heavy rainfall, but as the region shifts into El Niño, rainfall diminishes and there can even be severe drought (Lander, PEAC Report). The yellow bars indicate declared El Niño and the red bars indicate a strong El Niño. Guam had a declared El Niño in: 2002-2003, 2004-2005, 2006-2007, 2009-2010 and a strong El Niño in 2015-2016 (Figures 4.1. and 4.10a).

Although sea surface temperature (SST) has no direct effect on aquifer responses to ENSO, SST is one of the parameters in the ENSO Index, and is thus shown in Figure 4.10a. SSTs vacillated between $25^{\circ}-30^{\circ}$ during this time series. The highest SSTs were seen when ONIs were at or above +0.5 and therefore occurred during El Niño years. This graph of ONI and sea surface temperature (SST) describes the regional climate conditions on Guam for this time series.

5.3.2. Sea level

Sea level is also influenced by ENSO. During El Niño years, mean sea level on Guam can be more than a foot lower than during La Niña or neutral years. For most of the study period (2000-2016), sea level has remained above mean sea level (amsl). The average sea level was 0.35 ft amsl (0.00 msl is set at the mean lowest-low tide). Sea level dropped below mean sea level in 2002-2003, 2004-2005, slightly in 2007 and 2009, and again in 2015-2016. These drops in sea level correspond to El Niño years. There is a slight effect on lens position as sea level drops but not enough to significantly affect the conclusions discussed here.

5.3.3. Rainfall

Daily, monthly and annual rainfall amounts were observed for this study. The average daily rainfall is 0.29 inches, however, there is a high degree of variability in daily rainfall amounts and rainfall is concentrated in the wet season. Daily rainfall amounts were used to calculate the 5-year running sum, which is shown by the orange line above the rainfall amounts (Figures 4.3a and 4.10a).

The average monthly rainfall on Guam is 8.7 inches, indicated by the dotted horizontal blue line (Figure 4.3b). The blue columns are months where rainfall exceeded 10 inches per month. Every year in this time series has months with higher than ten inches per month with the exception of 2000, 2008, and 2010. These three years had some months with higher than average rainfall but did not exceed ten inches per month.

The average annual rainfall on Guam is 100 inches (see Figure 4.3c), with a standard deviation of 22 in. During this time series, there were six years (2001, 2002, 2003, 2009, 2012, and 2014) of average rainfall (100-120 in), three years (2004, 2011, and 2015) of above average rainfall (>120 in), and eight years (2000, 2005, 2006, 2007, 2008, 2010, 2013 and 2016) of below average rainfall (80-100 in). Annual rainfall amounts have a definitive impact on Guam's aquifer. Years of higher than average rainfall result in Guam's freshwater lens thickening and years of drought show a thinning of the lens.

5.4. Vertical depth Frequency Analysis

Depth-frequency analysis (Figure 4.11) shows the frequency at which each groundwater interface occupies a given depth during this study period. A depth-frequency analysis was done for each deep observation well level (DOWL) except for the 25000 μ S/cm level, omitted for simplicity. The three levels of interest for this analysis are the water level (blue line), the bottom of the freshwater lens (BoFL) (green line) and the bottom of the transition zone (BoTZ) (red line). Also shown, is the production well depth zone consistent with depths of 25-40 ft bmsl, as suggested by Mink (1976) and CDM (1982).

5.4.1. DOW EX-7

Water level at EX-7 shows a likely normal distribution with a smaller mode (Figure 4.11.). Periods of drought would explain a lower than average water level and periods of high recharge would result in water levels being higher than normal. The distribution of this level indicates that water levels act as we would expect in response to recharge.

The BoFL shows a bimodal distribution in which one mode would correspond to the wettest period in this record (2000-2004) and the other mode to the driest period (2005-2009). One would expect the BoFL to rise during times of drought and to deepen during periods of high recharge.

There is a similar distribution for the BoTZ (red line). It is bimodal and would also correspond to the wettest and driest periods during this time series.

5.4.2. DOW GHURA-Dededo

Water level at GD has a positively-skewed distribution with several spikes which would suggest a more sensitive response to recharge. BoFL and BoTZ distribution for this well are very similar in shape: both showing two strong modes, with a third smaller mode a little deeper. These two deeper modes correspond to the 2004 period of abundant recharge,

indicating that GD may have a more dynamic storage capacity in response to high recharge events.

5.4.3. DOW EX-10

Water level at EX-10 has a likely normal distribution, indicating that this water level also behaves as we would expect in response to recharge (Figure 4.11.) The BoFL of this well differs from EX-7 and GD in that it has a normal distribution and is most often found at its average depth. This may be due to its position north of the axis of the Yigo Trough, and as a result has a more rapid response to recharge and faster discharge as well. The BoTZ, however, shows a bimodal distribution similar to EX-7. This would suggest that the BoTZ is more sensitive to recharge than the BoFL.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

This study is the first long-term study of NGLA lens dynamics. It was concentrated on a single basin with data from three deep observation wells (DOWs). The long-term, practical implications of this study are that lens dynamics for the entire aquifer can be measured, and the data used for sustainable management. This project is a flagship study that eventually aims to help address such frequently asked questions as: 1) During severe drought, how does the lens thin and how long does it take? 2) What is the sustainable yield of this aquifer?, and 3) How deep can we drill wells into the lens, and how hard can we pump those wells? This section lays out findings in the Yigo-Tumon Basin and recommendations for future studies.

6.1. Goals and Objectives

The goals and objectives outlined in Chapter 1 have been addressed and fulfilled. Data from the three DOWs in Yigo-Tumon basin, were collected, examined and organized to show multi-variable interactions that contribute to NGLA lens dynamics. Statistical analysis was done on the three DOWs to show lens behavior, transition zone response, and head-tosaltwater interface ratio for this portion of the aquifer. The Ghyben-Herzberg ratio was used as a guide to estimate depth of saltwater interface for the water-level wells, M-10A and M-11. Lens response to recharge was correlated to seasonal, inter-annual, and episodic changes in rainfall. Finally, recommendations are made about the applications of these findings in determining appropriate sustainable development strategies for the NGLA.

6.2. Summary of Aquifer Dynamics

The main determinant of lens behavior is annual recharge. The NGLA shows an obvious response to running annual variations in recharge. During periods of drought, the lens thins, and during times of recharge, the lens thickens. The lag time for thinning is twice as long as the lag time for thickening at all three DOWs (Table 5.1.). Each well in this study, however, has a unique lens response due to local geologic conditions. Overall response suggests that fast flow through the vadose zone is rapid and that there may be a fast percolation mode as suggested by Bautista (2017). Discharge is slower than maximum rates of recharge. Transition zone dynamics show a complex and varied response to variations in recharge and should be studied on their own.

6.3. Recommendations and Future Studies

Study of the other five basins is needed next, and our recommendations include installing DOWs in each basin to obtain a comprehensive NGLA lens history. This history will not only provide insight into lens dynamics (such as behavior during drought) but will also assist in future modeling of lens dynamics.

6.3.1. Observation well expansion

New well additions should be a coordinated effort between Guam Hydrologic Survey, Guam Waterworks Association, USGS and Department of Defense activities. The USGS can provide guidance and consultation on new well locations and assist with well rehabilitation. Eight new observation wells are planned to be installed by the Monitoring System Expansion and Rehabilitation Program (MSERP) (USGS/WERI Proposal: Groundwater Resources Program for the Northern Guam Lens Aquifer, 2016-2025) and to be maintained by the One Guam Aquifer Monitoring Program (OGAMP) which will be administered by USGS and WERI (Figure 6.1.).



Figure 6.1. Planned expansion and rehabilitation of observation wells (MSERP). Blue box symbols are sites for new DOWs (8 total) and yellow-filled circles are existing observation wells that will undergo rehabilitation.

The new wells are expected to be operational by the end of 2020. The already existing wells are to be rehabilitated and subsequently maintained by the CWMP, and jointly administered by USGS/WERI. Wells should be located in areas of easy access for monitoring and maintenance purposes and at least 4000 ft from the shoreline.

CTD and continuous water-level monitors should be placed in each DOW to obtain more accurate and precise information about lens response to recharge events. Quarterly monitoring does not show rapid lens responses to periods of high or intense recharge such as during tropical storms and typhoons. Continuous monitoring of these wells would give a more detailed and better understanding of responses and lag times.

Production well depth has historically been 25-40 ft bmsl based on recommendations from the Northern Guam Lens Study (CMD 1982). This appears to be conservative given that the BoFL of all three DOWs is always below 80 ft bmsl during this study. This study does not, however, consider the dynamics of saltwater intrusion that may arise from production pumping changes.

6.3.2. Groundwater modeling

Modeling analysis will also benefit from the continued study of lens history and dynamics. This study provides empirical data to which modeling results can be compared and history matched. Understanding actual lens behavior allows modelers to better predict lens response to future climate events and conditions.

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