Dynamic Response of a Freshwater Lens to Natural Variations in Recharge

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Abstract* — *The hydrographic analysis of a composite island aquifer's phreatic zone with climatic effects on contributing hydrologic processes provides insight to a freshwater lens' storage capacity. The observation wells in the Yigo-Tumon Aquifer Basin in the Northern Guam Lens Aquifer (NGLA) was scoped to conduct an empirical hydrologic study that characterized the dynamic response of the lens to natural climate variations. Results showed the actual thickening and thinning of the lens in response to rainfall and drought. This is the most comprehensive hydrographic analysis of the NGLA, capitalizing on decades of data collection through the Guam Hydrologic Survey and Comprehensive Water Monitoring Program. The techniques here may be applicable for determining capacities in similar aquifers.

Index Terms—freshwater lens, island karst aquifer, phreatic zone

I. INTRODUCTION

Freshwater lenses in unconfined island karst aquifers have a dynamic response to contributing hydrologic processes. A significant process is rainfall that infiltrates to recharge the freshwater lens. Guam (Fig. 1) has the Northern Guam Lens Aquifer (NGLA) with observation wells and influential hydrologic information that demonstrates phreatic zone dynamics for such aquifers. A hydrographic analysis of observation wells was organized to determine the types of hydrologic and climate factors that contribute to the thinning or thickening of the lens.

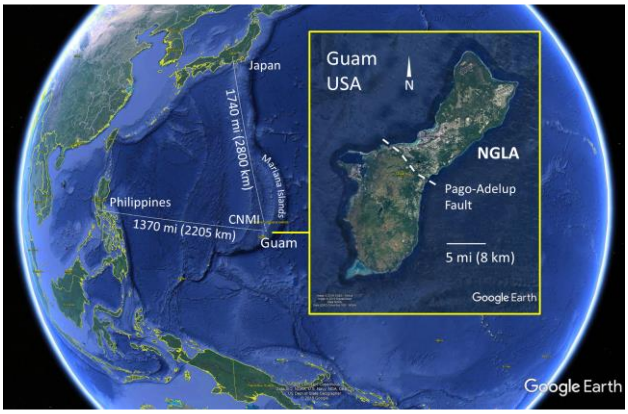

Figure 1. Guam USA, southernmost and largest of the Mariana Islands, in the Western Pacific. The Northern Guam Lens Aquifer (NGLA) is the physiographic region north of the Pago-Adelup Fault.

The goal was to characterize the response of the phreatic layers to natural, interannual and decadal-scale 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. Specific objectives were to define the anatomy as phreatic interfaces/layers, extract deep observation well data of phreatic interfaces and arrange data into a time-series as a hydrographic analysis aligned with potentially contributing hydrologic processes.

The scope were observation wells in the NGLA's Yigo-Tumon Aquifer Basin [16] (Fig. 2) that has three deep observation wells (DOWs) that penetrate the freshwater lens into the saltwater beneath (Fig. 3), and with water level (DOWLs): EX-7, GD (GHURA-Dededo), and EX-10. This study was limited to DOWLs, not obseration water level (OWL) wells: M-10A, M-11, and MW-2. The delimitations are the DOWLs in the domain, available meteoric, tidal, and climate index. The variables of interest are water level, freshwater lens, transition zone thickness, and seasonal lens thickness dynamics.

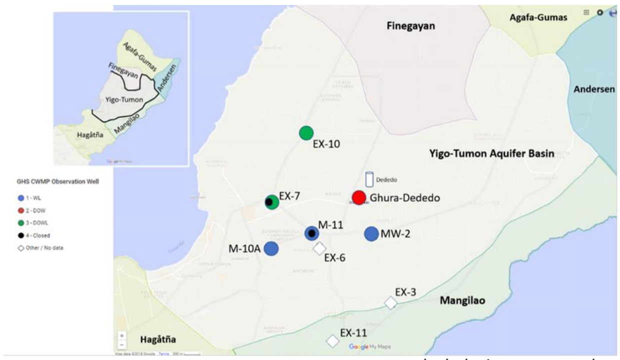

Figure 2. Yigo-Tumon Aquifer Basin, NGLA.

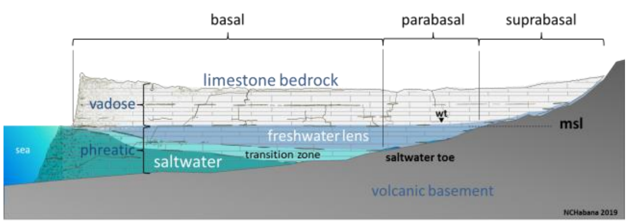

Figure 3. Schematic diagram of the NGLA.

II. BACKGROUND

1997-98's Epic El Niño (peak Oceanic Niño Index of 2.26) had a post-peak prolonged dry season, drought, that threatened water resources in the Western Pacific islands, including Guam. Soon after, two Guam Public Law (P.L.) Programs were enacted to observe and analyze the island's water resources: Comprehensive Water Monitoring

Acknowledgements: Funded by the Guam Hydrologic Survey and Comprehensive Water Monitoring Program (CWMP) in cooperation with US Geological Survey's Pacific Islands Water Science Center, Honolulu, Hawaii, via CWMP, administered through the Water and Environmental Research Institute, University of Guam.

Program (CWMP, P.L. 24-161) and the Guam Hydrologic Survey (GHS, P.L. 24-247). The program determined the continued collection of observation well data, as done earlier through *Northern Guam Lens Study* [3] which spanned from 1982 to 95 [6]. With nearly two decades of observation data since the two public laws, it was determined that a phreatic hydrographic analysis and interpretation would provide insight to the freshwater lens response. This will ultimately contribute to determining the sustainable management of the island's water resources.

A. Yigo-Tumon Aquifer Basin, NGLA

An aquifer is a natural porous material that captures, stores, and releases water in economically significant quantities. The US Environmental Protection Agency (USEPA) designated the NGLA (1978) as the primary source of utility water on Guam [15], currently supplying up to 90% of Guam's fresh water, 42 MGD (159 K·m^3/d). Yigo-Tumon is the largest of six aquifer basins in the NGLA, with the most production wells, yielding over 20 MGD (76 K·m^3/day).

The Yigo-Tumon aquifer basin is unconfined and classed *Composite* under the *Carbonate Island Karst Model* [10]. In cross-section view (Fig. 3), the aquifer has three laterally distributed freshwater zones: *basal*, area of freshwater ontop of transition salt water spanning the shore to the saltwater toe; *parabasal*, area between the saltwater toe and basement at mean sea level (msl) ontop of underlying basement; and *suprabasal*, freshwater beyond msl in the bedrock and on the basement.

B. Aquifer Basin Geology, Hydrology, and Hydrogeology

The NGLA is composed of a tilted and uplifted, eogenetic, karstified, highly permeable, limestone bedrock plateau (200-500 ft, 60-180 m) atop a much less porous volcanic basement rock. Yigo-Tumon aquifer core is of *Barrigada Limestone* that is exposed at the surface, in the middle, and peripheral rock of much younger *Mariana Limestone* [14, 12].

The aquifer has undergone karstification that most of the intense precipitation runoff into surface depressions and infiltrate quickly into the epikarst and drain into sinkholes. Surface permeability is high, such that surface streams are efemeral [9]. Jocson et. al. [7] found that during wet conditions, hydraulic head can rise within hours, which suggests the rapid lens recharge during intense storms [11].

Vertically (Fig. 3), the aquifer has a thick vadose and phreatic zone. Jocson 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, flowing down through conduits during heavy storms (taking only a few hours), while gentle rainfall percolate through the matrix pores of the vadose zone, which can take months to years [9].

The phreatic zone is the observation of interest, as it contains the freshwater lens, freshwater-saltwater transition zone, and the underlying saltwater zone. Concentration of saltwater increases with depth, as revealed in DOW conductivity-temperature-depth (CTD) data—most rapidly in the transition zone. The freshwater lens is an irregular lenticular freshwater layer, floating on top of the denser saltwater base, that discharges at the coast. The depth and thickness of this transition zone changes as the lens thins or thickens. DOW CTD profiles revealed that some sites can change to be thicker than the freshwater lens [8].

C. Freshwater Lens dynamics

Lens dynamics in the NGLA are driven by meteoric recharge, discharge, and sea-level. Simard et al. [13], however, observed wells in the NGLA, found that not all are equally influenced by these factors. Recharge is dependent on rain infiltration, 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. 7, 5]. The dry season and prolonged droughts have much less rainfall, thus much less recharge. Partin et al. [11] 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, depending on hydraulic conductivity, frequency, and altitude of the tidal/sea level signal. Tidal-signal and water-level relationships have been observed in some observation well data. Ayers et al. [2] and Rotzoll et al. [18] used tide and observation well data to estimate regional hydraulic conductivity. Olsen et al. [18] observed tidal signals attenuating to wells, using Fourier Transform analysis to interpret patterns and functions.

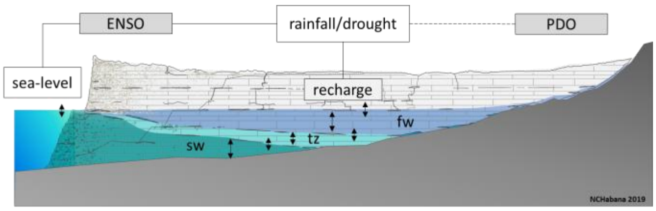

Figure 4. Schematic diagram of contributing hydrologic processes on phreatic zone dynamics.

Major climate events may drive the deviation from average seasonal patterns of meteoric recharge and tide. One well known climate event that reaches to influence the Western Pacific region interannually, affecting duration and intensities of rainfall and drought, including the long period of deep drop and high rise of sea level, is the El Nino Southern Oscillation (ENSO), which includes La Niña that may follow. ENSO status is observed and determined with Oceanic Niño Index (ONI). Another older method, but less preferred, is Sea Surface Temperature (SST). Climate hazards, during El Niño's interannual onset, peak, and post peak is illustrated in Fig. 5. El Niño, onset to peak, brings in heavy rain and tropical cyclones; at peak drops to a very low daily average sea level; into post-peak prolonged drought; and towards the end a rising sea level. El Nino's

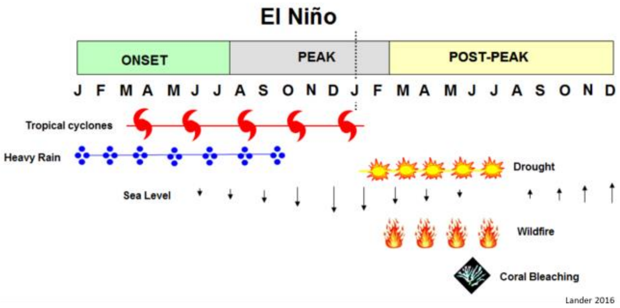

Figure 5. Climatic hazards on Guam, due to El Niño.

effect on the region is the result of changing winds and currents. Another climatic influence, inter-decadal low rainfall, is possibly Pacific Decadal Oscillation (PDO). Occurrence of interdecadal, nearly 10 years of low daily rainfall (5” or 102 mm) is possibly due to PDO.

D. CWMP and Observation Wells

Water and Environmental Research Institute (WERI) of the Western Pacific, University of Guam, and Pacific Island Water Science Center (PIWSC), US Geologic Survey (USGS), through the CWMP have measured and collected nearly two decades of observation well data in the NGLA. Wells on Guam are either production wells or observation wells [2]. 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) (Figs. 2 and 6).

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 CTD loggers. The data are downloaded from the loggers and are processed for quality and verified by USGS standards.

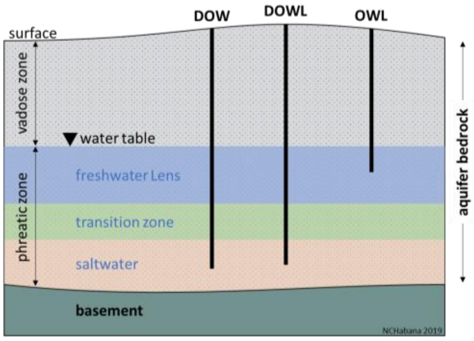

Figure 6. Observation wells. Deep observation well (DOW), measures CTD and water level – quarterly (at most), DOWL is a DOW with water level loggers, OWL is level loggers only.

II. METHODS

Specific objectives were to collect the best available data, define phreatic layers, apply phreatic hydrograph analysis, and interface depth statistical analysis to each DOWL. Microsoft Excel® was mainly used to organize data and apply graphical analysis.

A. Data sources

Observation well and climate data are available from online sources (REFERENCES, *Data sources*). Observation well data are from CWMP, GHS, and USGS PIWSC. Rainfall data are from National Climatic Data Center (NCDC) Climate Data Online (CDO) and USGS, ONI are available from NOAA, and sea level data is from the NOAA gage in Apra Harbor. The data span for this study is from 2000-2016.

B. The anatomy of the phreatic zone

Several salinity profiles from EX-7, GHURA-Dededo (GD), and EX-10, were graphed and examined for patterns and characteristic shapes (Fig. 7.). The USEPA secondary standard for freshwater (250 mg/L Cl^-/1100 µS/cm) was used as the definition of freshwater for this study. The transition zone was sub-divided into brackish, saline, and saltwater based on definitions from *The Glossary of Hydrology* [17].

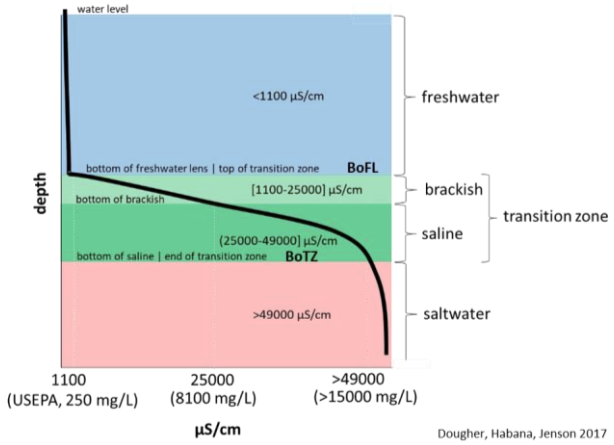

Figure 7. Salinity profile for defining phreatic zone anatomy. Terms also used are BoFL (bottom of freshwater lens) and BoTZ (bottom of transition zone).

C. Multi-variable time-series analysis

A multi-variable time-series analysis was developed to compare 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. 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.

D. Interface depth frequency analysis

A vertical frequency analysis of observation well interfaces was developed for each DOW in the Yigo-Tumon basin. A histogram analysis was done for each interface, water level and transition zone, sans the brackish-saline interface, and are displayed in the *Results and Discussion*.

III. RESULTS AND DISCUSSIONS

The results are in two figures. First is the hydrographic analysis of the phreatic zone aligned with contributing hydrologic processes, and second is the statistical analysis of the depths of the anatomy of the phreatic zone. The resulting figures are then followed by discussion, respectively.

A. Contributing hydrologic processes and lens Hydrograph

In Fig. 8, 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, from 2000-2016, minor ticks-marks are 6 months, and the smallest time record is daily: rainfall, average sea level, water level, 5-yr running sum of rainfall (orange line, secondary axis). ONI, as El Niño/La Niña intensity, 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 zones, and lens thickness. Water level is either by daily logger, or periodic points of 1/yr to 7/yr intervals. Transition zone include the Ghyben-Herzberg 40:1, derived from periodic water level, as estimated depth of freshwater and saltwater (yellow line in transition zones). Elevations (in feet, 1 m = 3.28084 ft) are shown for hydraulic head and transition zone boundaries. Lens thickness is the difference between the measured hydraulic head and BoFL.

B. *Vertical frequency analysis*

Fig. 9 is DOW graphs with elevation (vertical axis) and frequency distribution (horizontal axis) of the phreatic interfaces for water level, BoFL, and BoTZ. Other information includes average Ghyben-Herzberg depths and basic borehole information for each well, and its nearest distance to shore.

C. *Discussion of the phreatic hydrograph (Fig. 8)*

The ONI provides a record of the occurrence of El Niño (ENSO) conditions for Guam. Guam's location to this phenomenon dictates the amount of rainfall the island receives. El Niño years were: 2002-2003, 2004-2005, 2006-2007, 2009-2010 and a strong El Niño in 2015-2016. This graph of ONI and sea surface temperature (SST) describes the regional climate conditions on Guam for this time series.

Sea level is also influenced by ENSO. During El Niño years, mean sea level on Guam can be more than a foot lower, above average during La Niña 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.

Daily rainfall amounts were observed for this study. The average daily rainfall is 0.29 in (1 in = 2.54 cm), 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.

The average annual rainfall on Guam is 100 in, with a standard deviation of 22 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. In June 2004, Typhoon Tingting delivered more than 20 in of rainfall. Tingting was in a back-to-back El Nino, 2002-2006. Very soon after Tingting, was 9 years of very low rainfall. "The Big Nothing," (years 2005-2009) yielded yearly less than 4 in/day; and years 2010 to mid-2013, precipitation was less than 5 in/day. "The Big Nothing" period showed thinning of the lens observed in all three wells. Right after, the lens began to thicken, suggesting the annual daily rainfall rates, pivot of thinning-thickening. These years of low rainfall and lens thinning may be a result of PDO.

In June 2004, the freshwater lens at EX-7 was 113 ft thick, 3 ft thicker than average (110 ft). It reached its thickest, 126 ft, in December 2004 over a lag time of about six months, thickening at an average rate of 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 ft/yr. This suggests that recharge from the surface flows quickly to the lens during periods of high rainfall. Discharge from the lens, however, is slower. The 5-year running sum of rainfall displays an interesting relationship with lens thickness, and the pivot of thinning-thickening, and peak thickness.

In June 2004, the freshwater lens at GD was 129 ft thick, 4 ft thicker than the average thickness of 125 ft. 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. 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 which might explain their similar thickening and thinning behaviors.

In June of 2004, the freshwater lens at EX-10 was 104 ft thick, very close to the average of 103 ft thick. 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.

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).

D. *Discussion for interface depth-frequency analysis (Fig. 9)*

Water level at EX-7 shows a likely normal distribution with a smaller mode. 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

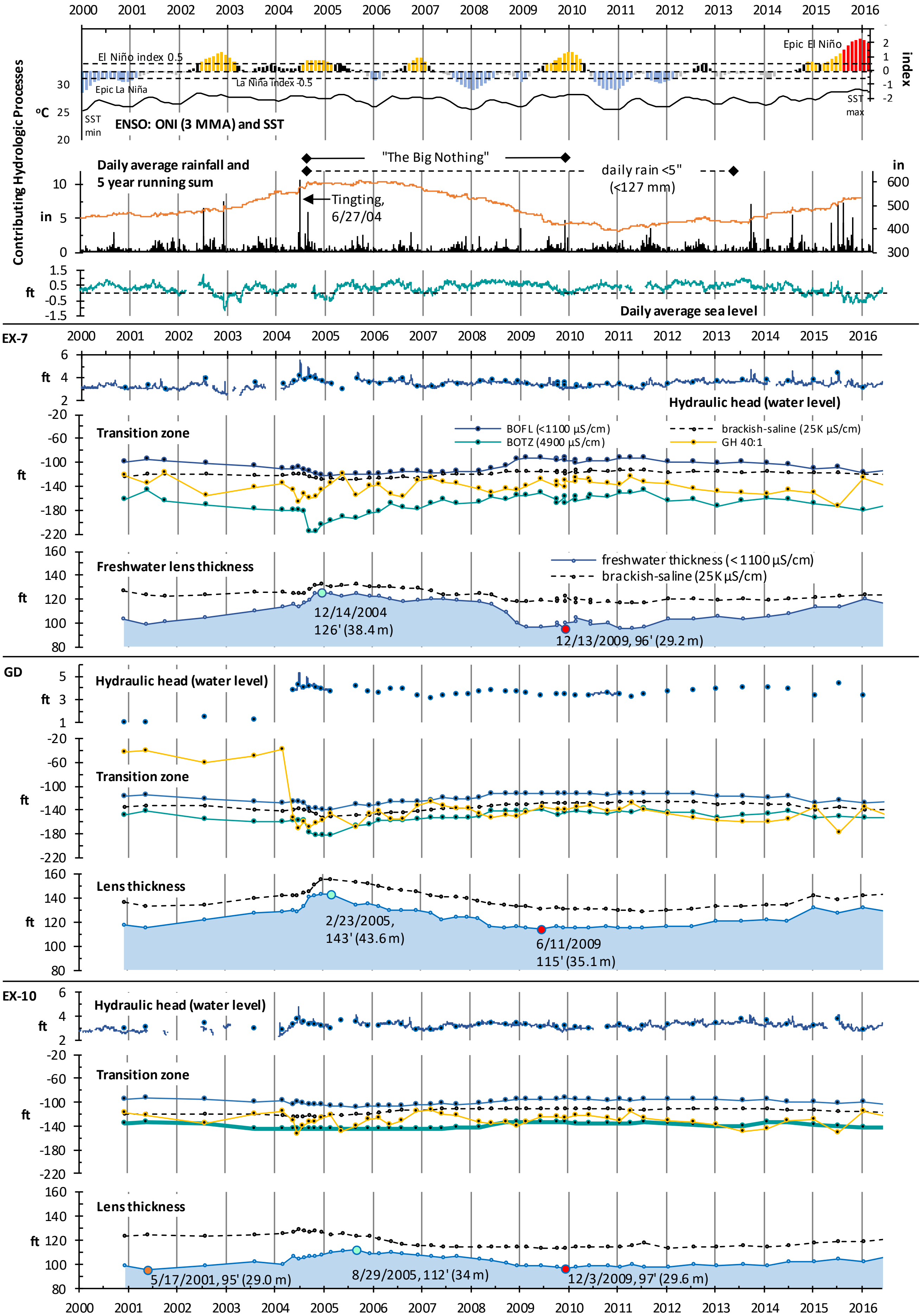

Figure 8. Multi-variable lens hydrograph analysis. Contributing hydrologic variables aligned in a time-series hydrograph of the phreatic anatomy. Observation wells EX-7, GD, and EX-10 graph of hydraulic head, transition zone, and lens thickness.

(1 m = 3.28084 ft)

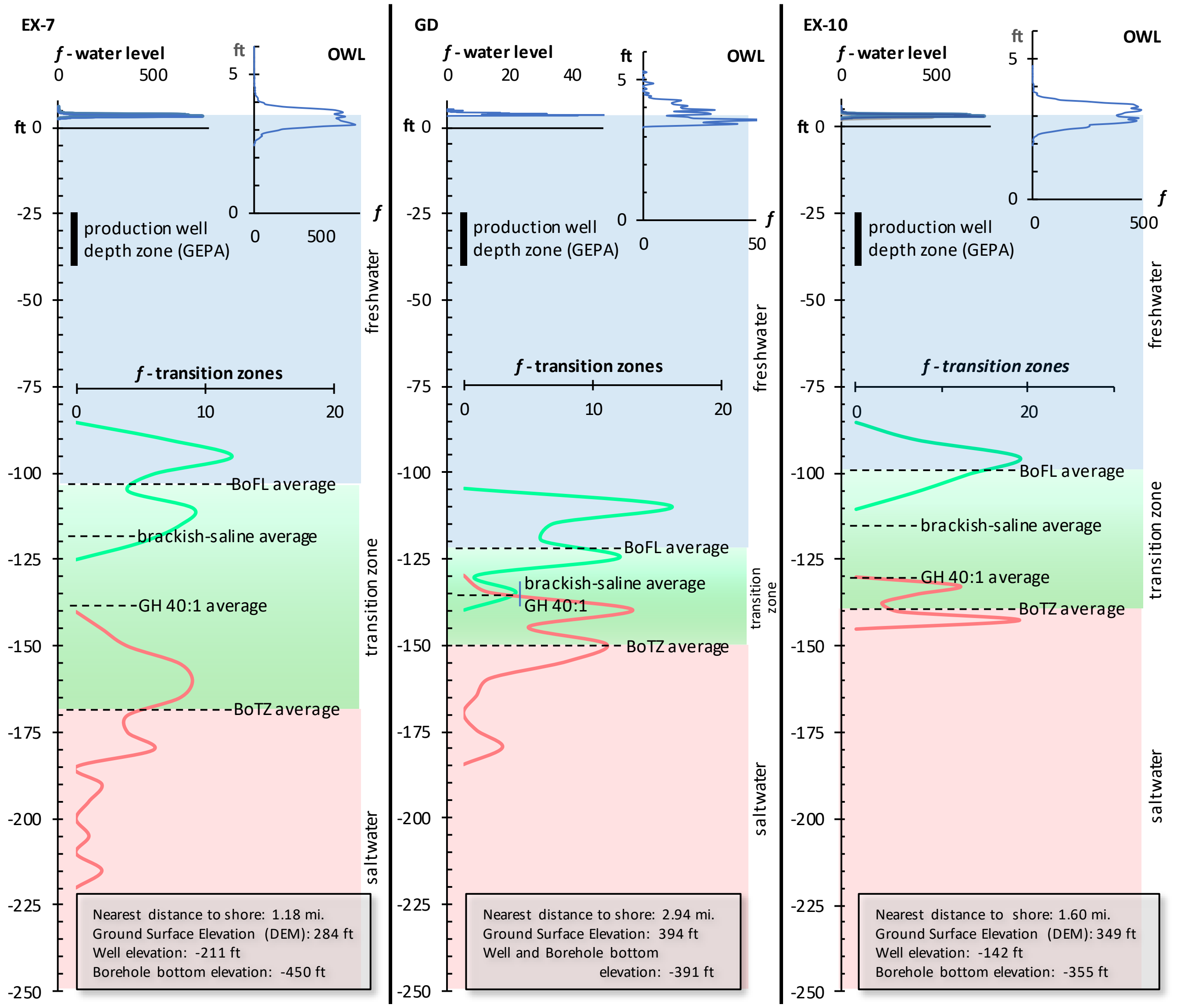

Figure 9. Frequency analysis of phreatic interface elevations. Horizontal axes are depth frequency, top axis for water level, and transition zone axis at -75 ft (23 m).

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. EX-7 has the thinnest freshwater lens measured of the three DOWs, 126 ft (Fig. 8).

Water level at GD has a positively-skewed distribution with several spikes, suggesting 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. GD has the thinnest average transition zone and the thickest average freshwater lens of the three DOWs.

Water level at EX-10 has a likely normal distribution, indicating that this water level also behaves as expected in response to recharge. The BoFL of this well differs from EX-7 and GD in that it has a normal distribution occurring often 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. EX-10 has the thinnest average freshwater lens of the DOWs in this study.

IV. CONCLUSION 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.

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. 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. 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.

Study of the other five basins is next, and our recommendations include installing DOWs in each basin to obtain a comprehensive NGLA lens history. This will not only provide insight into lens dynamics (such as behavior during drought) but will also assist in future modeling of lens dynamics. This research may serve as a model, graphing historic lens dynamics, retrodicting aquifer models, and as an addition to determining sustainable management of groundwater resource for similar aquifers.

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Data sources

USGS, Water Data for the Nation: https://waterdata.usgs.gov/nwis; **EX-7:** http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=133119144491771; **GD:** http://waterdata.usgs.gov/nwis/inventory?agency_code=USGS&site_no=133120144505471; **EX-10:** http://waterdata.usgs.gov/nwis/inventory? agency_code=USGS&site_no=133119144491771

NOAA, National Climatic Data Center (NCDC), **Climate Data Online** (CDO): **Rain:** https://www7.ncdc.noaa.gov/CDO/cdoselect.cmd?datasetabbv=GSOD&resolution=40 | National Center for Environmental Information: **Sea Level, ONI, and SST**: https://www.ngdc.noaa.gov

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Guam Pubic Laws, CWMP (P.L. 24-161) and **GHS** (P.L. 24-247): http://www.guamlegislature.com/24th_public_laws.htm

USGS PIWSC, US Geological Survey Pacific Island Water Science Center: https://www.usgs.gov/centers/piwsc