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ANALYSIS OF SALINITY IN THE NORTHERN GUAM LENS AQUIFER

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ABSTRACT. The Northern Guam Lens Aquifer (NGLA) currently provides about 80% of the potable water for the Pacific island of Guam. Protecting water quality has been a major concern since systematic aquifer development began at the end of World War II. This study comprises a comprehensive analysis of 38 years of NGLA salinity data to identify spatial patterns and temporal trends, and potential correlation with aquifer management practices and natural variables, including long-term rainfall, mean sea level, and Southern Oscillation Index.

Chloride remains the primary proxy for NGLA salinity. Chloride concentrations in groundwater showed significantly increasing trends at about two-thirds of the production wells. Notably, a cyclical chloride trend was observed at many production wells, exhibiting a 4-7 year periodicity that resembles the El Niño Southern Oscillation signal. Also, increasing salinity in the supra-basal zone, which is not hydraulically connected to saltwater suggests that non-saltwater sources of chloride, such as dissolved salts in rainfall, sea spray, or man-made sources, are affecting water quality.

Specific conductance data at seven deep monitoring wells were used to evaluate two designated depths of groundwater salinity within the NGLA: the lowermost extent of freshwater with ≤250 mg/l chloride, termed the *prime layer*, and the midpoint of the *freshwater-saltwater interface*, defined as the 50% seawater isochlor (27,000 mg/l chloride). The prime layer and freshwater-saltwater interface depths both displayed thinning trends between 2005 and 2010. These may result from a combination of below-average rainfall and rising sea levels, along with increasing pumping rates in some places. In the argillaceous limestone adjacent to the southern highlands, the prime layer, and to a dampened extent the freshwater-saltwater interface, exhibit seasonal fluctuations that greatly exceed those seen in the cleaner limestone units.

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INTRODUCTION

Guam is the largest and southernmost of the Mariana Islands in the western Pacific Ocean, being about 48 kilometers long by 6-19 kilometers wide. The northwest-southeast trending Pago-Adelup fault divides Guam into two physiographic provinces, a southern volcanic upland, and a northern limestone plateau overlying a volcanic basement (Figure 1). The northern limestone plateau slopes to the southwest with steep cliffs reaching 60-180 meters elevation, flanked by narrow coastal terraces.

The limestone units of northern Guam comprise the Northern Guam Lens Aquifer (NGLA). The principal water-bearing units are the Mio-Pliocene Barrigada Limestone and the Plio-Pleistocene Mariana Limestone (Tracey et al., 1964). The volcanic basement (Alutom Formation), underlying the limestone aquifer is orders of magnitude less permeable and can thus be considered an aquitard. The Barrigada Limestone is a massive, generally friable, deep-water foraminiferal detrital limestone deposited atop the volcanic basement (Tracey et al., 1964; Mylroie et al., 2001). The Barrigada Limestone forms the core of the aquifer, and grades upward and outward into the Mariana Limestone, a

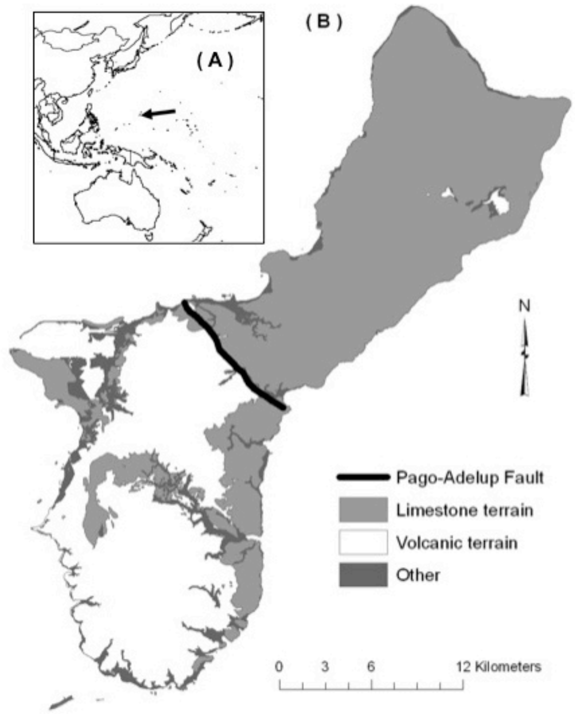


Figure 1. Study area. A) Location of Guam. B) Simplified geologic map of Guam, based on Tracey et al. (1964).

recrystallized and heterogeneous reef and lagoonal deposit that caps and flanks most of the northern plateau (Tracey et al., 1964; Mylroie et al., 2001). The Mariana Limestone is divided into two distinct members: the main member, uncontaminated by clay, and the Hagåtña Argillaceous member which contains up to 5% clay in the matrix, with pockets and cavities containing up to 20% (Taboroši, 2006).

The northern Guam limestones have not been extensively compacted or cemented, but have undergone extensive freshwater diagenesis (Jocson et al., 2002) and exhibit pervasive dissolution features (Mylroie et al., 2001). Dissolution by freshwater moving through the eogenetic limestone complex has created a triple-porosity aquifer, in which matrix, fracture, and conduit porosity all play substantial roles in groundwater storage and transport (Vacher and Mylroie, 2002). Hydraulic conductivity within the NGLA span large ranges on local and regional scales (Mink, 1976; Mink and Vacher, 1997; Rotzoll et al., 2013). Estimated hydraulic conductivities are ~20-800 m/day for wells on the periphery of the plateau and ~2,000-90,000 m/day for wells in the interior (Rotzoll et al., 2013).

A schematic cross-section of the NGLA is shown in Figure 2. A freshwater lens forms within the limestone aquifer where groundwater floats on denser saltwater (basal zone), or overlies the volcanic basement aquitard (para-basal and supra-basal zones). Within the *basal* zone, the 50% seawater isochlor, taken as the depth closest to 27,000 μS/cm specific conductance (seawater: 54,000 μS/cm) marks the midpoint of the transitional section, and is thus defined here as the lower limit of the freshwater lens. The intersection of the 50% seawater isochlor with the basement aquitard is called the *saltwater toe*. Within the *para-basal* zone, the freshwater lens is underlain by basement aquitard below mean sea level. Within the *supra-basal* zone, the freshwater lens is underlain by basement aquitard above mean

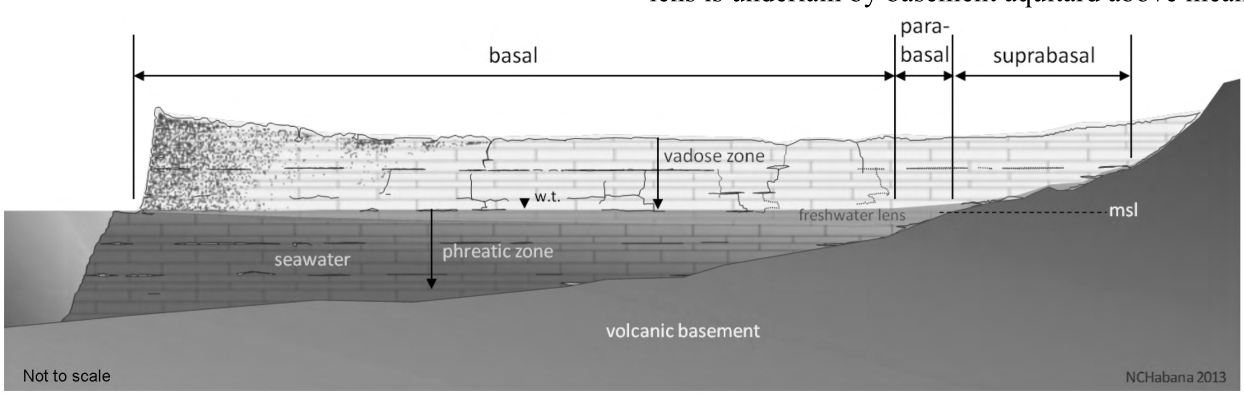


Figure 2. Cross-sectional schematic of the Northern Guam Lens Aquifer (from AECOM Technical Services, Inc., 2011; revised by N. Habana, 2013).

sea level (AECOM Technical Services, Inc., 2011).

Guam receives about 254 cm (100 inches) of rainfall per year: 70% during the wet season from July to December, and 30% during the dry season from January to June (Lander, 1994). Past recharge studies suggest about 40% of total rainfall over the NGLA is lost to evapotranspiration while the remaining 60% is captured as recharge (CDM 1982; Jocson et al., 2002). A recent Guam water budget study completed by the USGS estimates that recharge to the NGLA may be lower, at 51% of mean annual rainfall, or about (124 centimeters (49 inches) per year (Johnson, 2012). Rainfall infiltrates the limestone either through diffuse flow during light to moderate rainfall events or concentrated fast flow through fractures and conduits during heavy rainfall events (Jocson et al., 2002). Rainfall onto the much less permeable volcanic terrain of Mt. Santa Rosa and Mataguac Hill enters the subsurface via streams that sink at volcanic-limestone contacts (Taboroši et al., 2005).

Hundreds of boreholes have been drilled into the NGLA since the United States Navy brought the first drill rig to Guam in 1937 (McDonald and Jenson, 2003; Simard et al., 2012). In 1974, 57 production wells were extracting approximately 15 million gallons per day (MGD) from the NGLA (Mink, 1976). By 2009, 136 production wells were extracting approximately 43 MGD from the NGLA (Simard et al, 2012). The NGLA monitoring well network consists of seven deep monitoring wells installed in 1981-1982 and rehabilitated in 2000, two test borings advanced in 2010, and four failed production wells converted to monitoring wells (Jenson and Jocson, 1998; AECOM Technical Services, Inc., 2011).

METHODOLOGY

To analyze NGLA salinity in this study we compiled over 38 years of recorded chloride concentrations from production wells and 6 years of specific conductance data from deep monitoring wells. Figure 3 shows the well locations relative to the NGLA hydraulic basins (CDM, 1982) and estimated volcanic basement location at mean sea level (Vann, 2011). Chloride concentrations collected from 1973-2010 at production wells were provided by Guam Waterworks Authority (GWA), Naval Facilities Command Marianas, Guam Environmental Protection Agency, and the Water & Environmental Research Institute of the Western Pacific (WERI). Specific conductance data collected from May 2005 to November 2010 at seven deep monitoring wells were provided by the U.S. Geological Survey (USGS) Pacific Islands Water Science Center. Drilling and well construction logs, well operation permits, aquifer investigation reports, and pumping rates were also obtained from these agencies.

Water table elevations at each NGLA

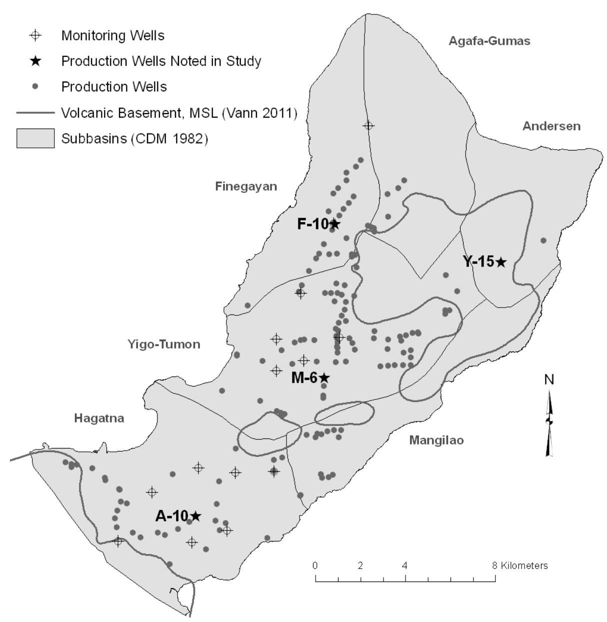


Figure 3. Production well, monitoring well, and volcanic basement mean sea level contour map of northern Guam. Sub-basin boundaries from the Northern Guam Lens Study (CDM; 1982 are still utilized for aquifer management purposes. Volcanic basement mean sea level contours based on Vann (2011, unpublished) (from Simard et al., 2012).

monitoring well were obtained from the National Water Information System web interface maintained by the USGS (USGS, 2011). Monthly rainfall data recorded at Andersen Air Force Base (AAFB) from 1953-2010 were obtained from the Global Historical Climatology Network Monthly dataset provided by the National Climatic Data Center (NCDC, 2011). Monthly mean sea-level measurements at Apra Harbor from 1960-2010 were obtained from the National Oceanic and Atmospheric Administration (NOAA) historic tide database (NOAA, 2011). Southern Oscillation Index (SOI) values from 1876-2010, as a proxy for El Niño Southern Oscillation (ENSO), were obtained from the Australian Bureau of Meteorology website (ABM, 2011).

Descriptive statistics and linear regression analyses of the chloride concentrations at each production well were conducted to evaluate temporal trends. Minimum, maximum, standard deviation, and decadal mean averages of the chloride concentrations were calculated for the intervals of 1973-1979, 1980-1989, 1990-1999, and 2000-2010. Pump rates were also graphically compared to the recorded chloride concentrations for each of the 153 NGLA production wells to reveal possible contributions of pump rate to NGLA salinity.

Using scatterplot graphs, chloride concentrations from select production wells representative of the basal, para-basal, and supra-basal NGLA groundwater zones were compared to the monthly rainfall data from AAFB, mean sea-level data from Apra Harbor, and SOI data recorded over the past few decades.

Chloride concentrations and specific conductance values from 3,800 GWA production well samples collected from 2000-2011 were correlated to determine the specific conductance equivalent to 250 mg/l chloride, the USEPA Secondary Drinking Water Standard for chloride. The resultant specific conductance value of 1,100 μS/cm, specific to the NGLA, was then applied to specific conductance data recorded at the deep monitoring wells to estimate the lower limit of the NGLA *prime layer*. The fluctuation of the prime layer over time, as well as the freshwater-saltwater interface, or 50% seawater isochlor, was evaluated for each deep monitoring well from May 2005 to November 2010.

RESULTS AND DISCUSSION

Chloride Trends

Of the 153 production wells cumulatively extracting about 43 million gallons per day from the NGLA, linear trend analyses of chloride concentration showed:

- an increasing trend in 107 wells (70%);
- no trend in 41 wells (27%); and
- a decreasing trend in 5 wells (3%).

A comparison of decadal average chloride concentrations from the 1970s, 1980s, 1990s, and 2000s revealed that the highest concentrations occurred in the 2000s at 85% of the wells. The 2000s experienced higher pumping rates and higher chloride concentrations than any of the previous decades at a majority of the production wells throughout all six basins. Moreover, chloride concentrations in the last two decades, compared to the first two decades, exhibited greater differences between the minimum and maximum during any given year. The addition of production wells over time (29 in 1970s, 35 in 1980s, and 25 in the 1990s) combined with increasing pumping rates at many production wells in the past few decades, may be contributing to the observed increased in salinity.

A cyclical chloride trend, with a periodicity of approximately 4-7 years, was observed at several production wells (e.g. F-10, Figure 4) in basal and para-basal zones. In the example of basal production well F-10, the cyclical chloride trend does not appear to be related to the pumping rate, which is relatively consistent over 32 years of well operations. Notably, the magnitude of the chloride peaks increase with each subsequent cycle, with six

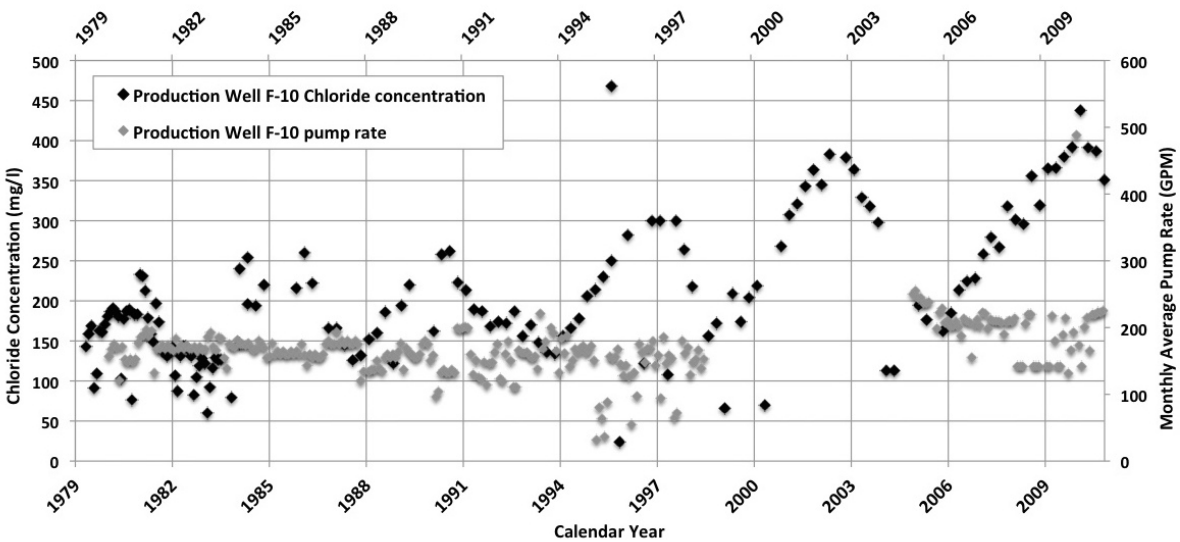


Figure 4. Chloride and production trends at basal production well F-10 in the Northern Guam Lens Aquifer. Example of cyclical chloride trend observed at production wells in the basal and para-basal groundwater zones.

peaks across the time scale and the last peak in 2010 (450 mg/l) more than double the initial peak in 1980 (200 mg/l).

Remarkably, eight of nine production wells situated in the supra-basal groundwater zone (Figure 2), an area of "perched" groundwater—having no contact with saltwater—exhibited increasing chloride concentrations since their installation in the mid-1990s. For example, supra-basal production well Y-15 (location shown in Figure 3), experienced a 55% increase in mean decadal chloride concentration between the 1990s and 2000s despite only a 6% increase in the mean decadal pump rate. Given that saltwater is not hydraulically connected with fresh groundwater in the supra-basal zone, sources of chloride other than saltwater, such as sea spray, airborne salt particles, and anthropogenic sources may account for increasing chloride trends.

Hydrologic Variables

Correlation between annual rainfall and mean annual chloride concentrations in production wells was observed at all three groundwater zones. Figure 5 shows chloride concentrations at basal production well A-10 compared to the departure of annual rainfall from mean annual rainfall recorded at AAFB from 1973-2010. The chloride trend is relatively stable until 1989, and then doubles from 200 to 400 mg/l by 2010. Relatively sharp increases in chloride occurred from 1989-1994 and 2006-2010; the former corresponding to periods of average to below-average annual rainfall, and the latter corresponding to five consecutive years of below-average annual rainfall. Most production wells across the basal, para-basal, and supra-basal zones exhibited increasing chloride trends from 2006-2010, with 207 centimeters (81 inches) less rainfall than average over that five-year period. Since 1973, the cumulative effect of several consecutive years of below-average or above-average rainfall appears to have a greater effect on groundwater salinity (based on chloride trends) than one isolated anomalous year.

Sea level has been recorded since 1948 at Apra Harbor on Guam's western coast (Figure 6). The sea level at Guam and throughout Micronesia is strongly affected by ENSO, with lower sea level occurring during El Niño, and higher sea level occurring during La Niña. The ENSO variations of sea level are large, and are visibly the dominant signal of natural variability in the time series.

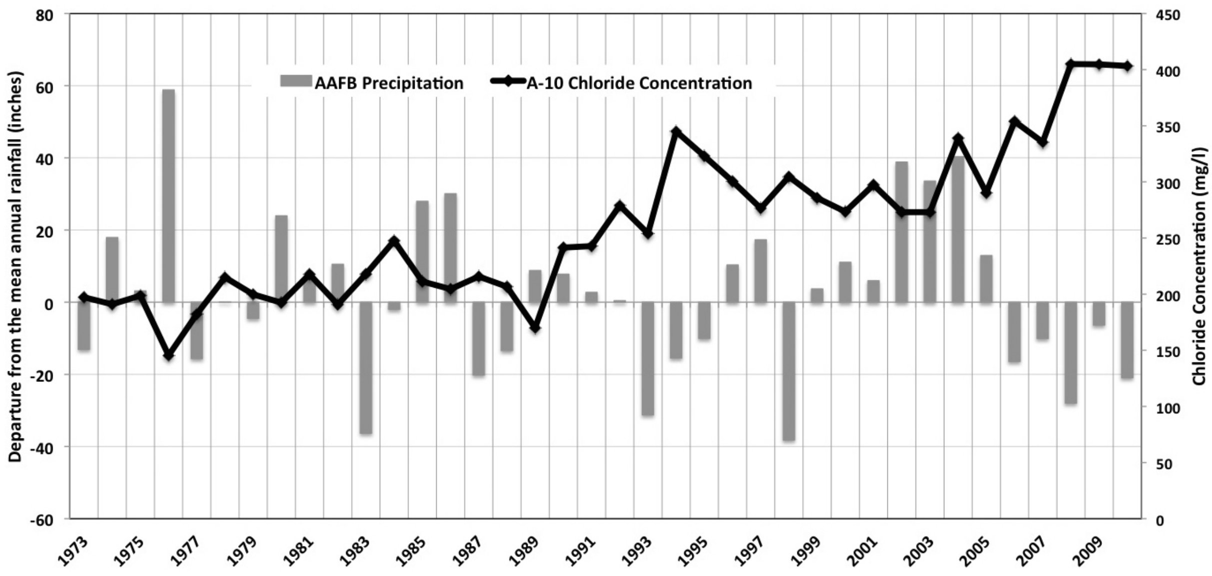


Figure 5. Departure of total annual rainfall from mean annual rainfall at Andersen Air Force Base compared to mean annual chloride concentrations at basal production well A-10 in the Northern Guam Lens Aquifer.

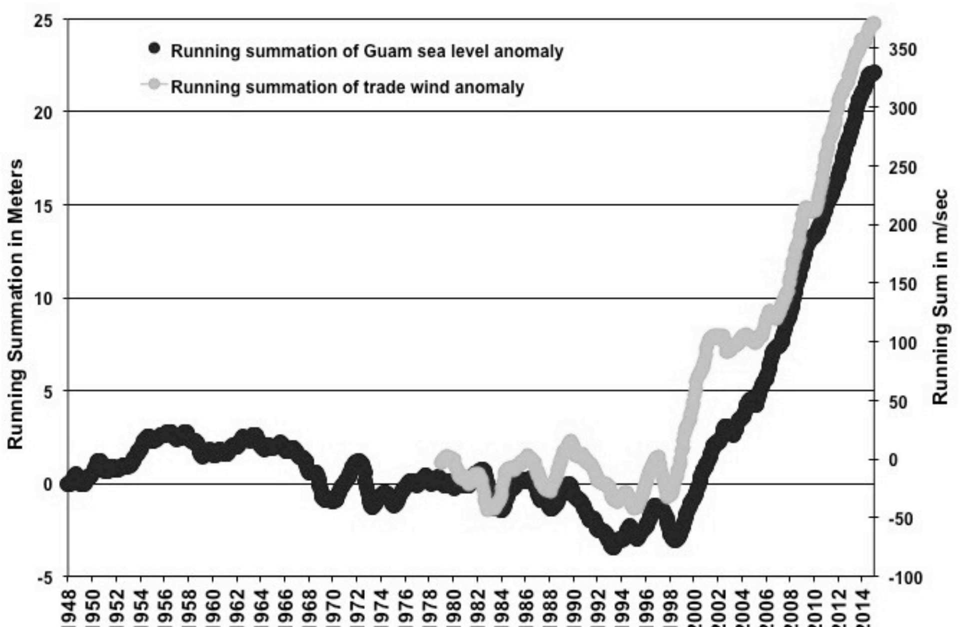


Figure 6. Running summation of the Apra Harbor mean sea-level and Pacific trade wind anomalies recorded from 1948 to 2014.

Another striking characteristic of the sea-level time series is best revealed by a running sum of the sea-level anomaly (Figure 6), that shows a dramatic "hockey-stick" increase of sea level for the years 1998 to present. For the period 1948 through 1997, there was no statistically significant long-term rise of sea level on Guam, or indeed, anywhere in the tropical western North Pacific. In 1997, it was still a bit of a mystery why the sea level had not shown an increase in this region. During 1998, however, the sea level rose dramatically, and stayed continually high thereafter. The step-function rise of sea level also manifests as a similar step-function increase in the strength of the Pacific trade wind system (Merrifield et al., 2012). This suggests the trade wind increase is the primary cause of recent sea-level rise on Guam and in the tropical western North Pacific. The change of decadal mean sea level was 12 cm between the 1990s and the 2000s. Figure 7 shows the average monthly mean sea-level measurements compared to the quarterly chloride concentrations at basal production well A-10 from 1973-2010. The chloride and mean sea-level trends closely parallel each other, with mirrored peaks and valleys across both datasets.

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

La Niña episodes, which were previously noted for very high sea levels, exhibit stronger Pacific trade winds, capable of carrying increased amounts of salt aerosols that serve as condensation nuclei for rainfall, and contribute dry salt deposits to the land surface. Increased wave activity and sea spray along the coastline may also add dry salt deposits across Guam. Diffuse or fast-flow recharge, with concomitant infiltration of dissolved salts, can occur on the order of months to hours, respectively, depending on the intensity and amount of rainfall (Jocson et al., 2002). Conversely, one might expect chloride concentrations in groundwater to decrease during transitions from La Niña to El Niño, as Pacific trade winds and regional sea levels subside and rainfall is often abundant.

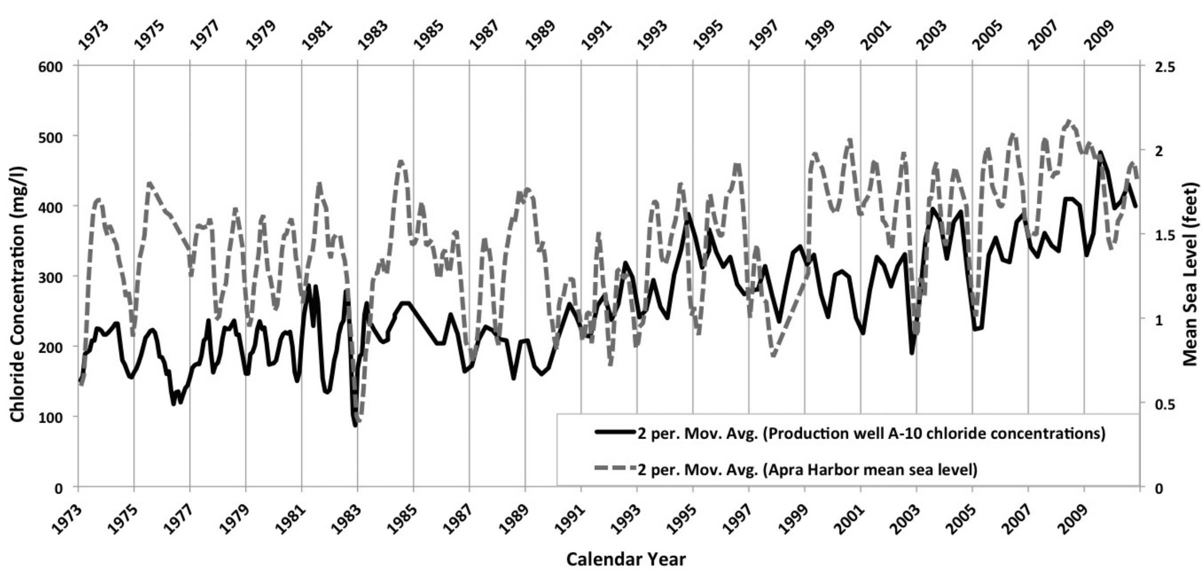


Figure 7. Average monthly mean sea level measurements at Apra Harbor (NOAA, 2011) compared to quarterly chloride concentrations at basal production well A-10 in the Northern Guam Lens Aquifer. Mean sea level and chloride concentration trends are shown in two period moving averages.

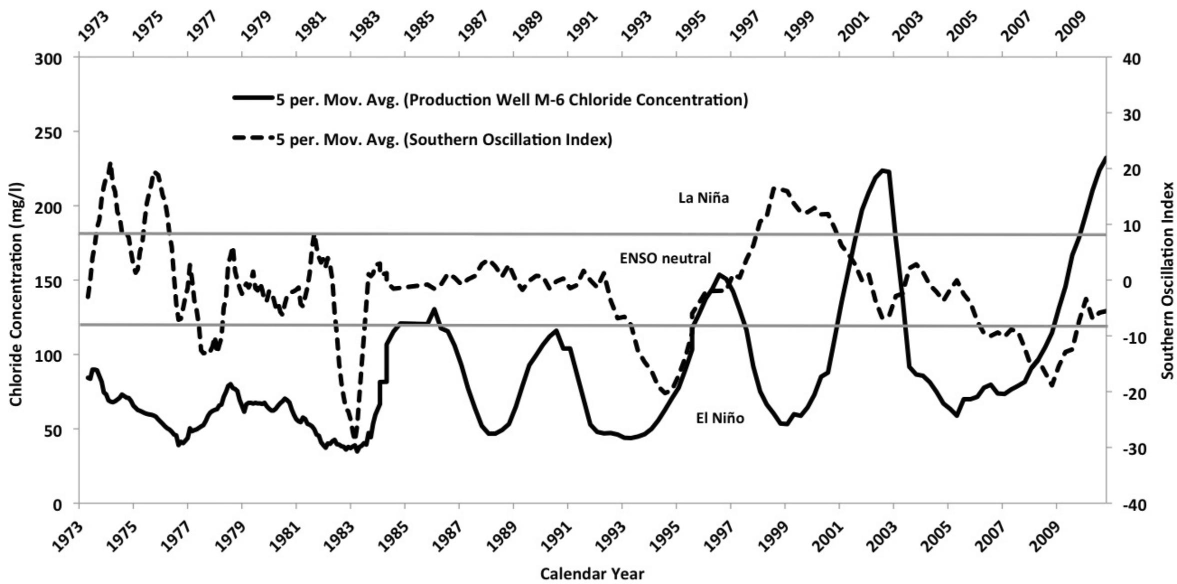


Figure 8. Southern Oscillation Index (SOI) values from the Australian Bureau of Meteorology (2011) and quarterly chloride concentrations at basal production well M-6 in the Northern Guam Lens Aquifer from 1990 to 2010. SOI and chloride concentration trends are shown in five period moving averages. Horizontal lines distinguish the El Niño Southern Oscillation episodes specific to the SOI values recorded at the Australian Bureau of Meteorology.

Freshwater Lens Response

Figure 9a shows the location of the seven deep basal monitoring wells that penetrate through the freshwater lens and are thus utilized for salinity profile measurements. Tracking the lower limit of the prime layer and 50% seawater isochlor using salinity profiles indicates a thinning of the freshwater lens between May 2005 and November 2010. Figure 9b and 9c illustrate the approximate lower limit of the prime layer and 50% seawater isochlor observed in these monitoring wells during this time period. (The lower limit of the prime layer is the depth closest to 1,100 µS/cm specific conductance.) At EX-1 and EX-4 in the Hagåtña Argillaceous Member of the Mariana Limestone, the prime layer fluctuated seasonally by as much as 70 meters between the wet and dry seasons. During the wet season, the great range of prime layer elevations at EX-1 and EX-4 suggests that seasonal recharge strongly influences the prime layer thickness in the Hagåtña Argillaceous Member. During the dry season, the shallowest prime-layer elevations are consistently about -17

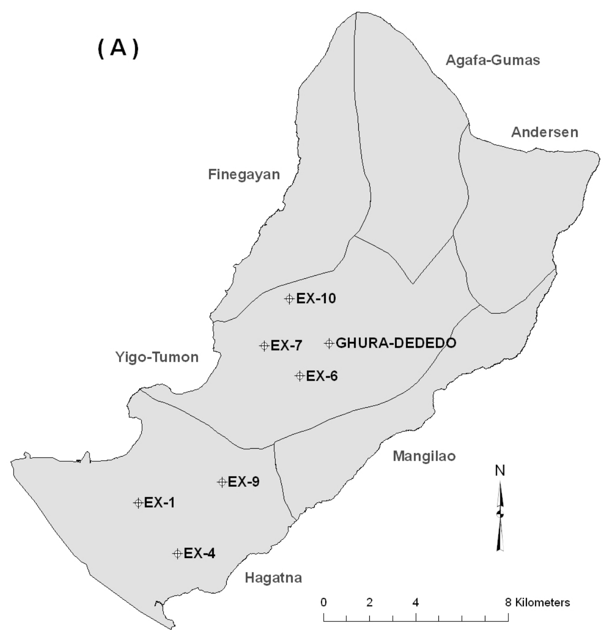
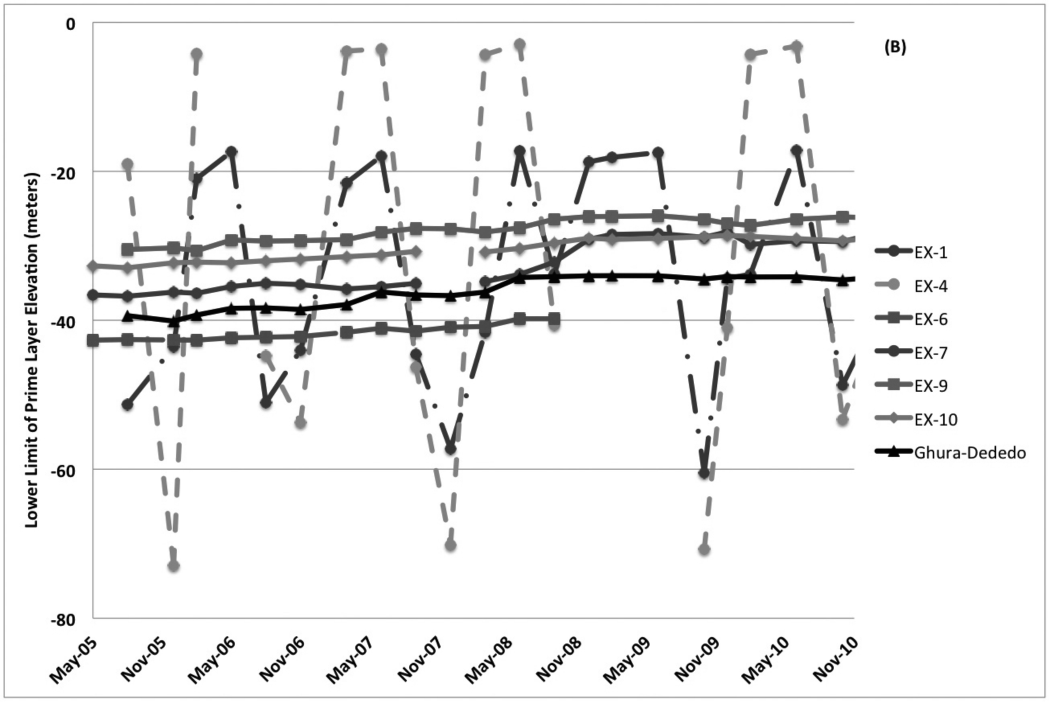


Figure 9. Prime Layer and 50% Seawater Isochlor Depths in the Northern Guam Lens Aquifer from 2005 to 2010. A) Location of deep monitoring wells in the Northern Guam Lens Aquifer utilized for salinity profiles. B) and C) continued on the following page.



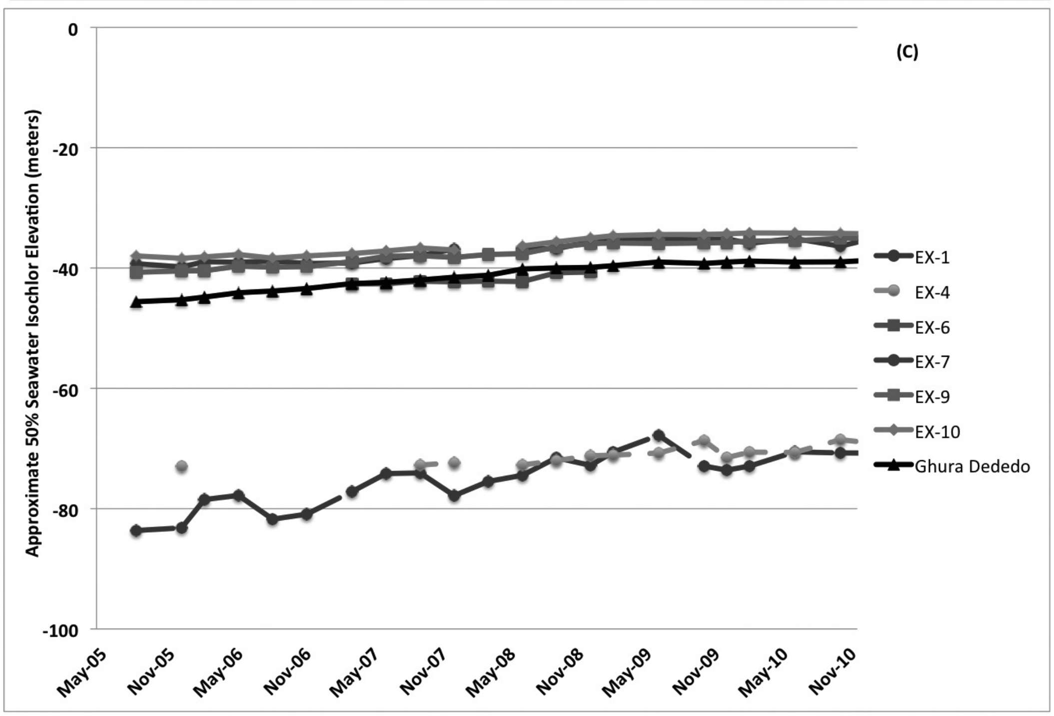


Figure 9 (cont. from previous page). B) Approximate lower limit of the prime layer (equivalent to 1,100 µs/cm specific conductance) observed at the deep monitoring wells. C) Approximate 50% seawater isochlor depth (equivalent to 19,000 µs/cm specific conductance) observed at the deep monitoring wells.

meters at EX-1 and -3 meters at EX-4. Consistent with past studies that have noted higher chloride concentrations at production wells in the Hagåtña Basin near EX-1 and EX-4 (Mink, 1976; CDM, 1982; Mink, 1992), this study indicates that production wells are extracting higher salinity groundwater when the prime layer becomes as thin as -3 meters elevation during the dry season. Of the five deep monitoring wells situated in the cleaner Barrigada and Mariana Limestones, the lower limit of the prime layer decreased in depth by 3-9 meters from 2005-2010.

Similar to the prime-layer depths, the approximate location of the 50% seawater isochlor at the seven deep monitoring wells reflects the hydrogeological difference between the Hagåtña Argillaceous Member and the cleaner Barrigada and Mariana Limestones. The proportion of clay contained in the limestone directly affects its permeability. The Hagåtña Argillaceous Member has lower permeability than the Barrigada and Mariana Limestones. The 50% seawater isochlor at EX-1 and EX-4 in the Hagåtña Argillaceous Member was almost twice as deep as the other five monitoring wells in Barrigada and Mariana Limestone. The seasonal fluctuation of the 50% seawater isochlor at EX-1 and EX-4 follows the prime layer fluctuations, only muted. Additionally, as the 50% seawater isochlor shallows and the saltwater toe migrates inland, production wells normally in relatively low-chloride para-basal zones come in contact with higher-salinity groundwater.

CONCLUSIONS

This study comprises the most comprehensive historical evaluation of data for the occurrence and factors contributing to trends in groundwater salinity in the NGLA. The observations reported in this study provide only a starting point for more detailed and focused research into the causes of salinity trends and patterns within the NGLA. Of particular interest are the relationships of groundwater quality to the ENSO cycle, and susceptibility of the NGLA to sea-level rise and drought. Further consideration should also be given to the role of structural elements (i.e., faults) and karst features (especially sinkholes) to NGLA salinity, as well as sources and variability of the mass budget of chloride across northern Guam.

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