Report for 2002GU1B: Groundwater Infiltration and Recharge in the Northern Guam Lens Aquifer during the record- breaking 1997-1998 ENSO event

There are no reported publications resulting from this project.

Report Follows:

PROJECT SYNOPSIS REPORT

Project Title

Groundwater Infiltration and Recharge in the Northern Guam Lens Aquifer during the record-breaking 1997-1998 ENSO event.

Problem and Research Objectives

The Northern Guam Lens Aquifer is comprised of Plio-Pleistocene limestone units deposited atop a volcanic basement. Typical heads range from about 3 to 5 feet above sea level, with the maximum thickness of the lens ranging up to about 150 feet. Continuously draining into the ocean, the water in the lens is replenished by rain, which, averages about 100 inches per year, but is highly variable on both long and short time and space scales. Guam draws some 80% of its drinking water from the freshwater lens in the aquifer, using some 45 million gallons per day, a bit more than half of the most recent estimate of 70-80 million gallons per day of sustainable yield. In order to identify appropriate techniques and management practices to sustain aquifer development while protecting water quality, groundwater scientists and engineers need a better understanding of aquifer dynamics. In particular, it is necessary to better understand the factors that control the rates and amounts of water taken into storage, the residence time of water in the aquifer, and the quantities that can therefore be extracted in given times and places without degrading the quality of the water. The responses of well levels to rainfall events provide important clues regarding the rate at which water descends through the vadose zone, the amount of time that it is retained in phreatic storage, and therefore the amount that may ultimately be available for exploitation by various techniques.

Variations in rainfall and sea level are the most direct and important causes of variations in well levels. Observations from 3 wells in the Agana Argillaceous Member of the NGLA indicate that the combined variations in sea level and rainfall in real time or near-real time account for up to 66% of the variance of water levels in the wells—the sea level accounting for the larger share of this variance near the coast, and the rain accounting for the larger share of the variance at well locations further inland. Multi-year variations of rainfall appear in the well levels at time lags up to nearly two years.

One of the most intense El Niño events of the past century occurred in 1997. Associated with this event there was a record number of very intense typhoons in the western North Pacific during 21997. Annual rainfall throughout Micronesia was heavy. Guam was struck by a devastating typhoon (Paka) in December of 1997. The following year, 1998, there was a record drought throughout Micronesia, with many places recording the lowest annual rainfall total. Rainfall gradually returned to normal in 1999-2001, with the annual amount at Guam increasing each year. The large spike of rainfall in 1997, followed by the extreme dryness of 1998 (Figs. 1 and 2), offered a unique opportunity to study the response of the northern Guam lens aquifer to such a dramatic natural event; especially the previous finding of a long-term lag of approximately 18 months to pass large variations of large-scale rainfall through the aquifer.

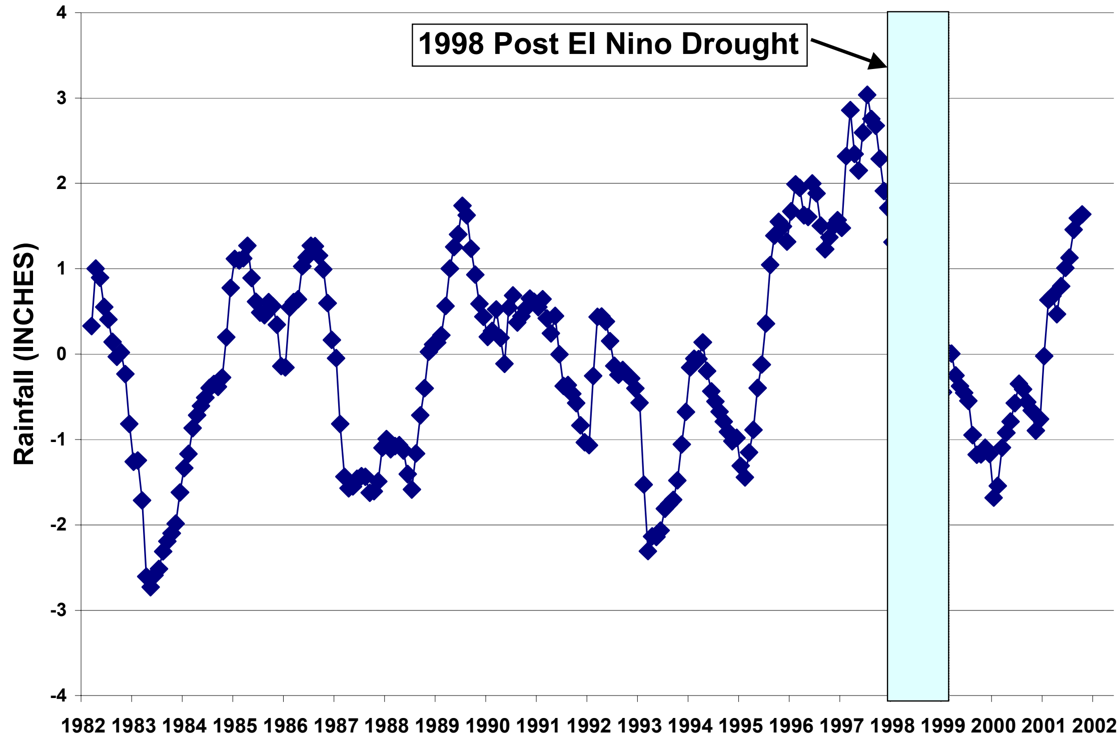
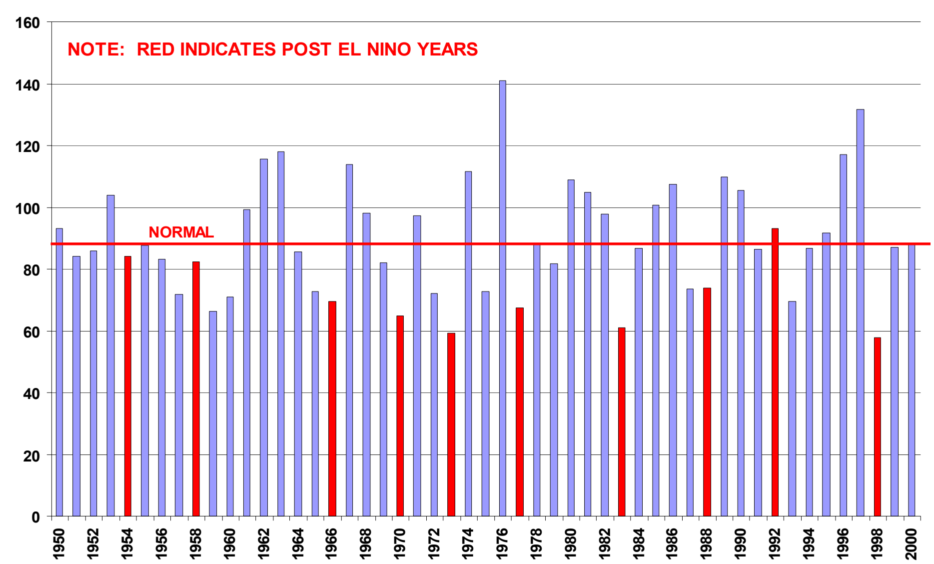


Figure 1. Monthly rainfall anomalies at Andersen Air Force Base. Blue box indicates the extreme dryness that followed the 1997 El Niño.

GUAM ANNUAL RAIN



NOTE: POST-EL NINO YEARS IN RED

Figure 2. Time-series of Guam annual rainfall at the Guam International Airport. Note the high rainfall in 1997 followed by record low rainfall in 1998.

Methodology

Removing the tidal signal in the well time-series

The correlation of well water levels with the daily and monthly mean sea level is in general a function of distance from shore. All water level time series of the NGLA exhibit statistically significant cross-correlations with the time series of the daily average tide (expressed in feet above mean sea level). The tidal signal is transferred rapidly into the aquifer, and cross-correlations are highest at zero time lag for all periods investigated (daily to monthly). At some wells, the variations of sea level account for upwards of 50% of the variance of the time series of daily and monthly average water levels.

The linear cross correlation value is used to remove the tidal signal from the well water level time series. The cross correlation coefficients between the sea level and the water level of a given well can be used in a linear regression to predict the value of one variable given the value of the other. The best prediction that a linear regression can yield is given by

$$(A_i)^* = (r)\,(s_A / s_B)\,(B_i)' + \overline{A} \qquad (1)$$

where: ( )* indicates the predicted value;
( )′ indicates departure from the mean value;
subscript i indicates the i^{th} value of the time series;
s_A and s_B are the standard deviations of variables A and B respectively;
r is the cross-correlation coefficient between variables A and B; and,
the over-bar indicates the mean value of the indicated time series.

Using Equation (1), the water level may be predicted from the sea-level time series. An adjusted well-level time series that is not correlated with the sea level may be obtained by subtracting the i^{th} term on the right-hand side of equation (1) from the i^{th} raw value of the well-level time series. In this manner, the well-level time series is "de-tided". Note that the well water level time series may be similarly adjusted to "de-rain" the time series, or to remove the component of any variable that has a non-zero cross-correlation with the water level. In this report, the sea-level signal was always removed first in order to evaluate the relationship of the remaining "de-tided" time series to the rainfall. Maximum correlations of water level with rainfall tended to occur at a time lag, whereas maximum correlations of water levels with sea level were always simultaneous at the frequencies examined (daily and monthly).

Using rainfall and tide to predict water levels

The "de-tided" water level time series may be cross-correlated with any other time series (such as time series of rainfall) to form a multiple linear regression equation of the form:

$$(A_i)^* = (r_{A:B})\,(s_A/s_B)\,(B_i)' + (r_{A:C})\,(s_A/s_C)\,(C_i)' + \bar{A} \qquad (2)$$

where: ( )* indicates the predicted value;
( )′ indicates departure from the mean value;
subscript i indicates the i^{th} value of the time series;
s_A, s_B, and s_C, are the standard deviations of variables A, B and C respectively;
$r_{A:B}$ is the cross-correlation coefficient between variables A and B;
$r_{A:C}$ is the cross-correlation coefficient between variable A (signal of B removed) and variable C; and,
the overbar indicates the mean value of the time series.

Such an equation derived to predict the level in well BPM1 from the rain and tide

$$(BPM1_i)^* = 0.5281\,(TIDE_i)' + 0.02227\,(RAIN_i)' + 2.723 \qquad (3)$$

yields a predicted time series for BPM1 that explains 66% of the variance of the raw time series. An investigation of the analysis of the variance explained by the rain and the tide (and the inter-relationships among other variables, such as the wind and the tide) at several well sites occurs in a later section.

Integrated anomalies

All of the variables examined in this report (rainfall, the Southern Oscillation Index or SOI, sea level, and water levels) were subjected to an analysis wherein the long-term annual or monthly mean of the variable is removed and the anomalies of each variable are added in sequence to create a time series of the running total. These running totals, or "integrated anomalies," sharply highlight long-term deficits or surpluses. The running totals of all the variables show prominent long-term deficits and surpluses that are clearly inter-related.

Residual analysis

Using the multiple linear regression equations, the well heads at several of Guam's observation wells was predicted (e.g., Fig. 3). The residuals of this prediction were examined, and it was found that they were not random, but had a slowly varying component of periods of over-prediction and under-prediction. Shifting the residual time series by 18 months provided a nearly perfect match with similar periods of rainfall surpluses and deficits (Fig. 4). Incorporating a time-lag component of 18 months for the rainfall in the regression equation increased R from +.63 to +.76 (Fig. 5)

The large variations in rainfall from 1997 to 1998 was seen in the well heads of the Northern Guam Lens Aquifer (Fig. 6). Note that the prediction equation using simultaneous anomalies of rainfall and sea level is not as good as an equation that incorporates an 18-month time-lag component.

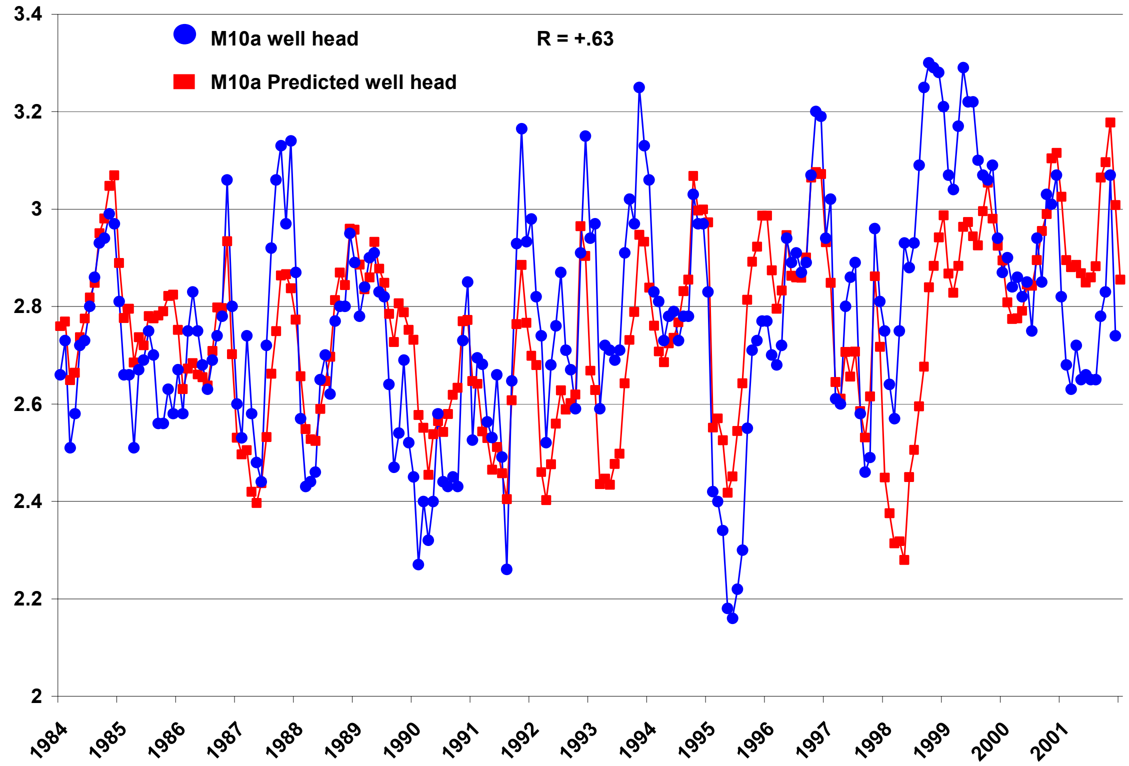


Figure 3. Prediction of well head from rainfall and tidal variations

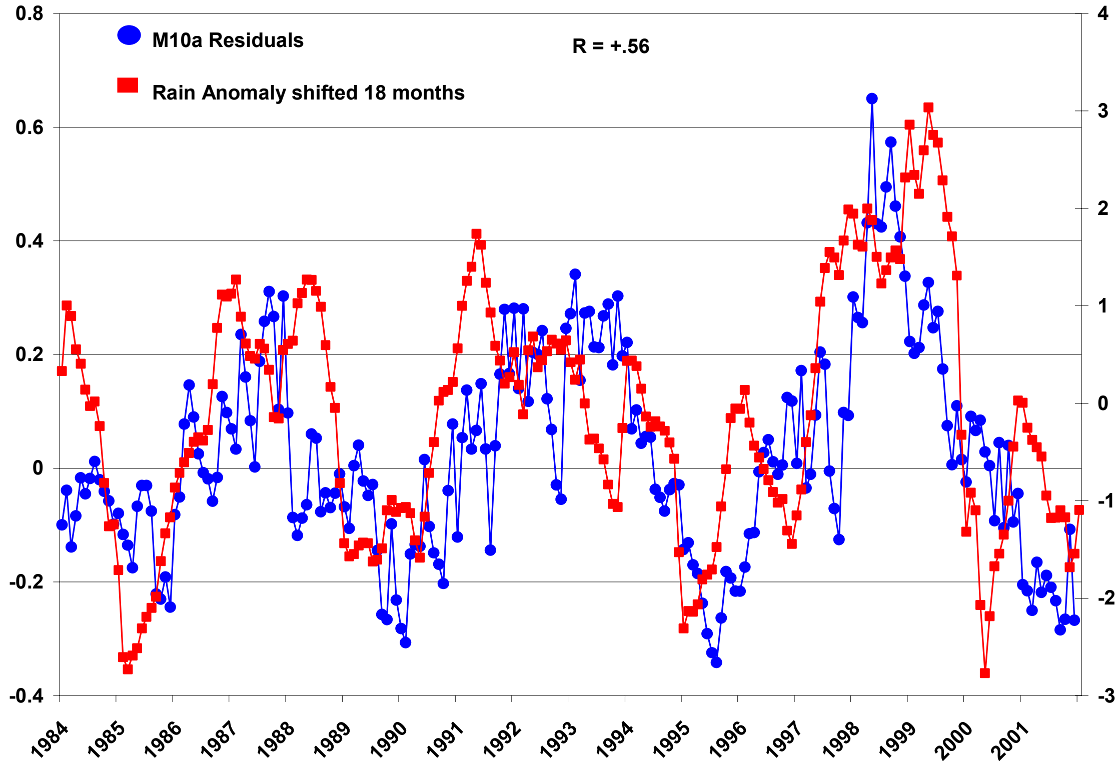


Figure 4. Residuals of well head prediction in Fig. 3 (shifted 18 months) versus rainfall anomaly.

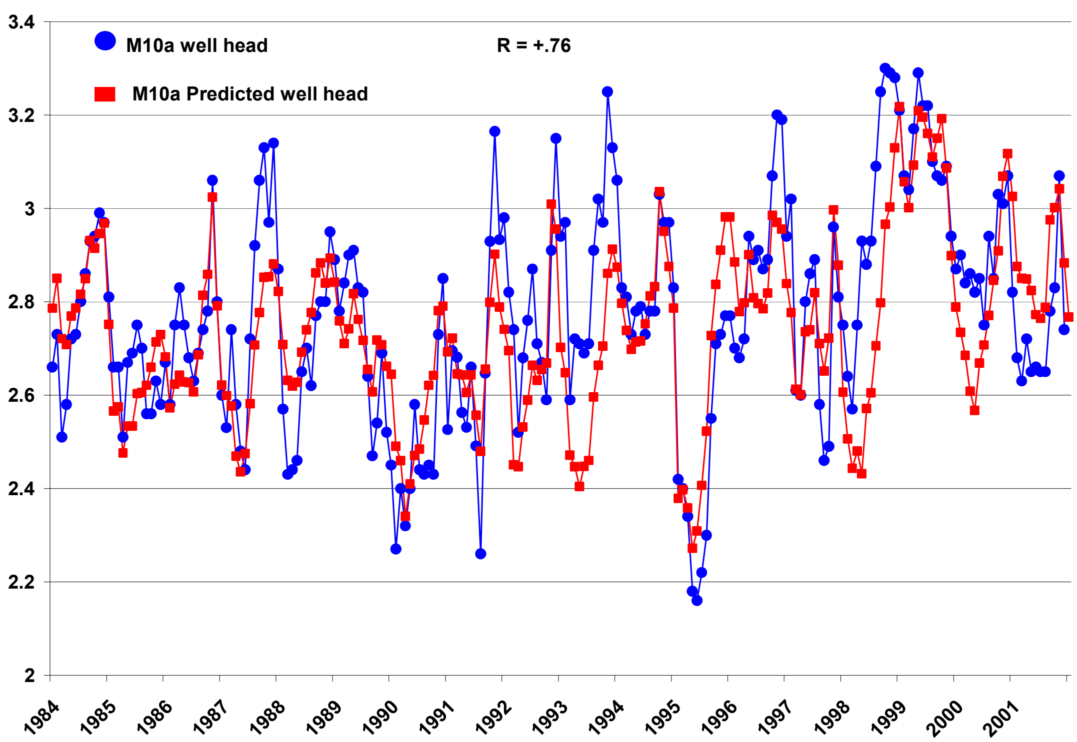


Figure 5. Predicted well head using rainfall and tidal signal plus a component from the rainfall anomalies at an 18 month time lag. Note the increase of R from +.63 in Fig. 3 to +.76.

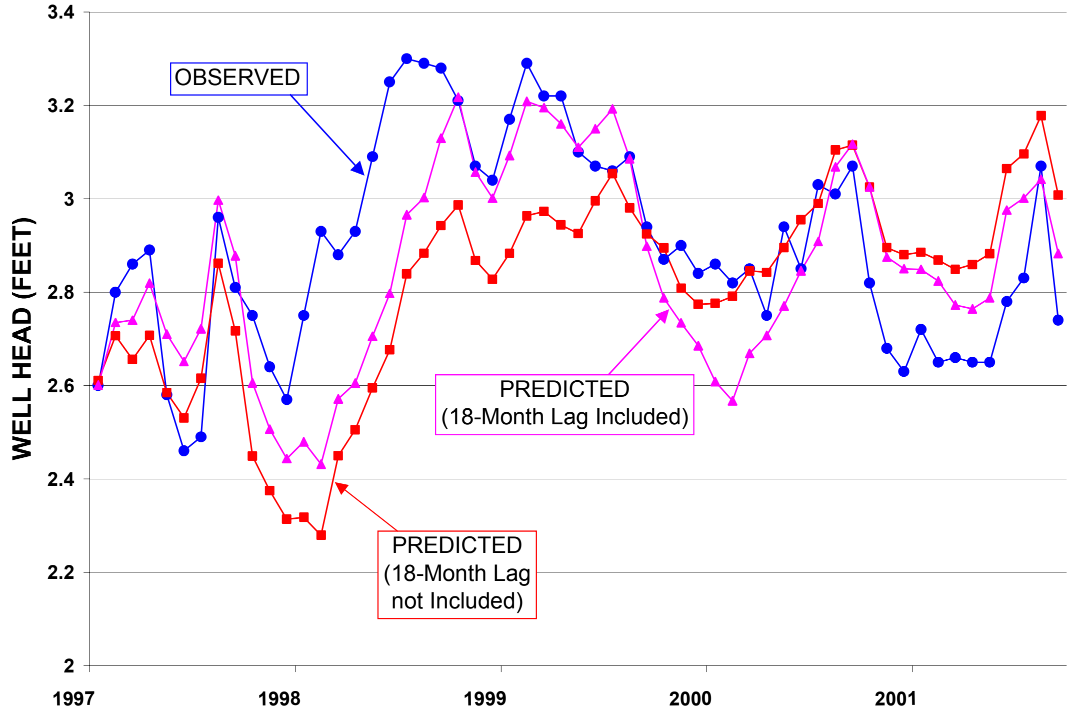


Figure 6. Well head time series showing the effects of the 1997-98 ENSO event. Note that inclusion of an 18-month time lag into the rainfall variable produces a better fit.

Principal Findings and Significance

The well heads of the northern Guam Lens Aquifer rise and fall with in concert with variations in both rainfall and sea level. The variance explained in the well heads by the combination of variations of rainfall and sea level approaches 70% for some wells. Analysis of the residuals of the predictions of well heads using variations in rainfall and sea level show a non-random sequence of under-predictions and over-predictions. The non-random variations in the time series of the residuals are highly correlated to similar deficits and surpluses of rainfall, but at an 18-month time lag. The huge differences in annual rainfall in 1997 and 1998 track into the well heads. The same 18-month time lag is noted. This project is still underway, and a comprehensive report will be forthcoming as a Master's Thesis and accompanying Technical Report in the Fall of 2003.