Estimating Hydraulic Properties for Volcanic Island Aquifers using Wave Setup
Problem and Research Objectives

As is the case in many parts of the United States and elsewhere in the world, water problems in Hawai‘i are related to the availability of potable freshwater and to its contamination by organic or inorganic chemicals associated with land-use activities. In Hawai‘i groundwater provides about 99% of domestic-water use and about 50% of other freshwater uses (Gingerich and Oki 2000). Although all the main islands have large amounts of groundwater contained in volcanic rock aquifers, the quality of some of this groundwater may not be suitable for all uses. While there is a great need to identify new sources for potable water, better management of the existing resources is equally important.

Aquifer management in Hawai‘i is based on the concept of “aquifer sustainable yield,” which is defined as the maximum allowable total daily pumping without compromising storage and water quality. When the sustainable yield is exceeded over periods of time the reduction in water storage can cause an increase in salinity (Meyer and Presley 2000, Oki 2005).

In fact, water-quality profiles in the Honolulu area show that the salinity of water in the aquifer has increased over the years and that the transition zone is undergoing a steady upward movement (Visher and Mink 1964, Oki 2005). The resident population has increased tremendously on all main islands in the last three decades and existing development plans will only further extend this trend. Hence, better management of the aquifers is essential to ensure sustainability of Hawai‘i groundwater resources.

Aquifer sustainable yield and management are studied by applying analytical and numerical models. Accurate values of hydrogeologic parameters, including hydraulic conductivity and storage, are needed for correct solutions. Uncertainty in correctly identifying the aquifer parameters may be reflected in erroneous model estimates—consequently leading to the potential mismanagement of drinking-water supplies.

Classic aquifer tests are accepted techniques for small-scale aquifer-parameter estimation. In such tests an aquifer is subjected to pumping and the water-table elevation level is recorded at the pumping well and in one or more monitoring wells. In Hawai‘i studies using aquifer tests to estimate hydraulic parameters include Williams and Soroos (1973), Gingerich (1999), and Rotzoll et al. (2007). However quantifying and removing all “background noise” (i.e., perturbations not directly related to pumping) from the water-level records is critical for accurate aquifer-test analysis.

Ocean processes can also have a significant influence on water-table elevations for unconfined coastal aquifers. Overlooking ocean influences when making groundwater assessments in near-shore aquifers can lead to unacceptable errors. Ocean tides, for example, represent a periodic high-frequency forcing affecting groundwater levels in coastal aquifers. The harmonic signal decays as it propagates through the aquifer as functions of transmissivity, storage coefficient, and distance from the shoreline (Jacob 1950, Ferris 1951).
Waves are another factor in near-shore water-table changes. The interaction between waves and the groundwater table below beaches and in the littoral zone is well known. Wave run-up on a sloping beach is characterized by an instantaneous swash infiltration resulting in groundwater responses in the beach zone (Li and Barry 2000). This drives a groundwater circulation where water infiltrates at the upper part of the beach and exfiltrates at the lower, submerged, part of the beach. Swashes that extend beyond the mean groundwater level cause the groundwater table to rise directly proportional to the amplitude of the wave run-up (Hegge and Masselink 1991). The amplitude becomes increasingly damped inland (Li et al. 1997) and is hardly detectable at distances greater than tens of meters away from the shoreline.

As with waves, periods of large ocean swells result in an elevated mean-water level at the shoreline. This condition is identified as “wave setup” (Longuet-Higgins and Stewart 1963). The super-elevation occurs from the effects of transferring wave-related momentum to the water column in the surf zone. The duration of such periods of large ocean swells is generally one to two days but can be longer. Existing studies relating wave-setup and groundwater-table variations were previously limited to beaches (Gourlay 1992, Turner et al. 1997, and Massel 2001). Investigations including aquifers further than 150 meters from the shoreline were previously unavailable.

Available data from Maui indicates that wave setup inside the Kahului Harbor, measured at the Kahului tide gauge, is less than that outside the harbor. Wave setup is a localized phenomenon greatly influenced by the bathymetry of the near-shore area (Holman and Sallenger 1985). Broad low-sloping beaches result in greater wave setup. On the other hand coastal areas fronted by pronounced channels generate less wave action. The presence of one or more channels allows water to flow back to the deeper ocean. In such areas the effects of wave setup are less intense.

The geometry of Kahului Harbor with its protecting breakwalls and its deep channel through the narrow entrance provides an example of the effects noted above. Waves do not generally break inside the harbor or in the channel. Thus less energy is transferred into the water column in the harbor and therefore the water level in the harbor is generally not substantially affected by wave setup.

The effects of ocean tides are commonly used in aquifer-parameter estimation (Merritt 2004, Trefry and Bekele 2004, and Rotzoll et al. 2008). However wave-setup responses have not previously been used in such endeavors.

Similar to addressing the effects of tidal responses, using data generated by wave setup in aquifer-parameter estimation offers an advantage over small-scale aquifer tests by providing information on greater length scales. In addition the use of wave-setup responses is appealing due to the lower costs and simpler logistics involved. The required observation period for groundwater-table fluctuations generated by wave setup is much shorter than that needed for observations of tidal variations. However wave-setup analysis requires a reliable swell forecast. Recognizing that usually accurate forecasts of large-swell events are generated five-to-seven days in advance of the event, it is generally possible to schedule wave-setup analysis during such an event.

The primary research objective of this study was to investigate the influence of large ocean swells and the resulting wave setup on low-frequency water-table variations in a coastal aquifer and to utilize wave setup in hydraulic-parameter estimation. The approach is expected to be beneficial to many high-permeability coastal environments such as volcanic islands and atolls. The technique will also provide a practical approach for aquifer-parameter estimation as an important step towards more efficiently managing valuable groundwater resources.
Methodology

A three-month period, starting on 11 December 2004, was chosen for the analysis because of the occurrence of high-energy swells observed in available data. Water-level data at four observation points in central Maui, located approximately one, two, four, and five kilometers inland from the island’s north coast near Kahului, had been collected at five-minute intervals by the U.S. Geological Survey.

Hourly-recorded climatologic data (barometric pressure and rainfall) were also available from the nearby Kahului airport. Available Kahului tide-gauge data provided tide readings every six minutes and available Waimea buoy data recorded significant wave height, dominant wave period, and swell direction every thirty minutes. Since the Waimea buoy is about 200 km away from the Kahului area a time shift between the arrival of the waves at the Waimea buoy and the study area was included in the analysis. For large waves traveling in deep water with a typical wave period of seventeen seconds, the time lag was approximately four hours (Brown et al. 1989).

To isolate and quantify the influence of wave setup on low-frequency water-table fluctuations we used different techniques of signal processing including low-pass filtering, spectral analysis, cross-correlation, and single- and multi-variable regression. Signal processing of the wave-setup data is required to filter out other environmental impacts, such as barometric and tidal influences, to limit the water-table fluctuation data recorded to that specifically generated by wave setup.

The effects of wave setup were correlated with observed inland transient-head changes. The water-table rise at the coast can be quantified by empirical formulae for wave setup controlled by the significant wave height, wave length outside the surf zone, and beach steepness (Stockdon et al. 2006). This allows relating the wave setup to the observed water-table rise in the aquifer and determining the efficiency of such measurements at each observation point as related to swells. Previously developed analytical solutions for tides were used to estimate aquifer hydraulic parameters (Jacob 1950 and Ferris 1951). The solution for the transient case, which assumes a vertical boundary between land and ocean, can be written as:

\[
h = h_0 e^{-\frac{x}{\sqrt{T_0 T}}} \sin \left( \frac{\omega t - x}{\sqrt{T_0 T}} \right)
\]

where \(h\) = water level in coastal aquifer (m), \(h_0\) = amplitude of the tidal harmonic oscillation (m), \(x\) = distance to coast (m), \(S\) = storativity (dimensionless), \(T_0\) = period of the harmonic oscillation (d), \(T\) = transmissivity (m²/d), \(\omega\) = angular frequency of the harmonic oscillation or \(\omega = 2\pi/T_0\) (d⁻¹), and \(t\) = time (d). This equation can be used to estimate aquifer diffusivity (T/S) based on either time lag or on attenuation of the signal.

The main contrast between tides and wave-setup pulse is that the wave-setup pulse is neither sinusoidal nor periodic. However during the data-collecting period a forty-one-day-long series of storm events occurred. This allowed the use of simple harmonics to describe the forcing. Spectral analysis identified the matching frequencies in wave-setup and groundwater responses. The aquifer parameters estimated from wave-setup propagation were compared with aquifer-parameter estimates from the same study area using aquifer tests (Rotzoll et al. 2007) and tides (Rotzoll et al. 2008).

Numerical modeling of the transient head using MODFLOW 2000 (Harbaugh et al. 2000) was applied to evaluate the accuracy of the analytical solution. A simple one-dimensional groundwater-flow model was developed including a wave-setup forcing at the boundary. The results of the numerical model were compared with those of the analytical model.
Principal Findings and Significance

The influence of wave setup on coastal-groundwater elevations and the possibility of using the propagating wave-setup signal in aquifer-parameter estimation were investigated for central Maui. The wave-setup signal is detectable at observation points as far away as five kilometers from the coast. Regression analysis shows that correlation coefficients between wave setup and groundwater fluctuations are as high as 0.73. The observation period was split into two sections, termed SWELL and BARO, to investigate the effects of wave setup and barometric pressure on groundwater levels. Observation of SWELL started on 12 December 2004 and lasted for 41 days and that of BARO started on 30 January 2005 and lasted for 35 days. The SWELL subset contains nine swell events, of which four were major storm events producing waves above 4 m. The SWELL subset was characterized by modest barometric fluctuations. In contrast the BARO subset shows more significant atmospheric pressure variations while wave setup is relatively uniform.

Barometric influence is insignificant (correlations <0.1) in the SWELL subset. However the correlation coefficients improve using setup and barometric changes together. In contrast, in the BARO subset, correlations with wave setup are weak and the influence of barometric-pressure variations is strong, reaching correlations up to 0.81. Therefore wave setup can significantly affect groundwater elevations in coastal aquifers and can overshadow barometric influence in times of large swell events. At other times the barometric loading dominates.

Wave-setup propagation through the aquifer is similar to that for tides with exponentially decreasing amplitudes and linearly increasing time lags between wave-setup and observed groundwater responses. The average duration of swell events in the SWELL subset was approximately 6 days and spectral analysis shows matching peak periods at 6.8 and 3.2 days in wave-setup and groundwater observations. The longer periods explain the milder amplitude attenuation and milder phase-lag gradients of wave-setup compared to tidal propagation. This can be very useful because wave-setup signals propagate deeper into the aquifer (about 10 km in central Maui) than diurnal tides (5 km) and can therefore provide information on greater length scales.

Aquifer parameters were estimated from wave-setup attenuation using the analytical solutions from tidal propagation. The results are consistent with parameters estimated from aquifer tests and tides in the same study area. Mean hydraulic diffusivity from wave-setup attenuation is identical based on the wave-setup estimates by Vetter (2007) and Stockdon et al. (2006) and is estimated as $2.3 \cdot 10^7$ m$^2$/d. Assuming that the wave-setup signal travels through the entire aquifer thickness of 1.8 km and the specific yield is 0.04, the hydraulic conductivity is 520 m/d.

A one-dimensional numerical model reproduced the results of the analytical solution. The best fit was achieved with hydraulic-conductivity values of 650 or 460 m/d, based on the respective approaches by Vetter (2007) and Stockdon et al. (2006). The model successfully simulated groundwater responses that match the transient head at observation points reflecting the amplitude attenuation and the time lag of wave-setup pulses. The mean correlation coefficient is 0.84 for all observation points.

Wave-setup signal propagation was successfully used to estimate hydraulic parameters. The technique is expected to be beneficial to many high-permeability coastal environments, such as volcanic islands and atolls, and will provide a practical approach for aquifer-parameter estimation as an important step toward managing valuable groundwater resources.
Publications Cited in the Synopsis


