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Estimating hydraulic properties of coastal aquifers using wave setup

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Summary Wave setup is the elevated mean water-table at the coast associated with the momentum transfer of wave breaking, which occurs generally over several days. Groundwater responses to wave setup were observed as far as 5 km inland in central Maui, Hawaii. The analysis showed that at times of energetic swell events wave-driven water-table overheights dominate low-frequency groundwater fluctuations associated with barometric pressure effects. Matching peak frequencies at 1.7×10^{-6} Hz and 3.7×10^{-6} Hz were identified in setup and observed head using spectral decomposition. Similar to tides, the setup propagation through the aquifer shows exponentially decreasing amplitudes and linearly increasing time lags. Due to the longer periods of setup oscillations, the signal propagates deeper into the aquifer (~10 km in central Maui) than diurnal tides (5 km) and can therefore provide information on greater length scales. Hydraulic diffusivity was estimated based on the setup propagation. An effective diffusivity of 2.3×10^{7} m^2/d is consistent with aquifer parameters based on aquifer tests and tides. A one-dimensional numerical model supports the results of the analytical solution and strengthens the suitability to estimate hydraulic parameters from setup propagation. The methodology is expected to be beneficial to high-permeability coastal environments, such as on volcanic islands and atolls.

Introduction

Various ocean processes including tides, wave runup, and wave setup can influence coastal groundwater tables. Wave setup is the wave-driven ocean water level overheight at the shoreline. The elevated mean water level occurs due to momentum transfer of breaking waves to the water column (Fig. 1). The cross-shore gradient of the radiation stress

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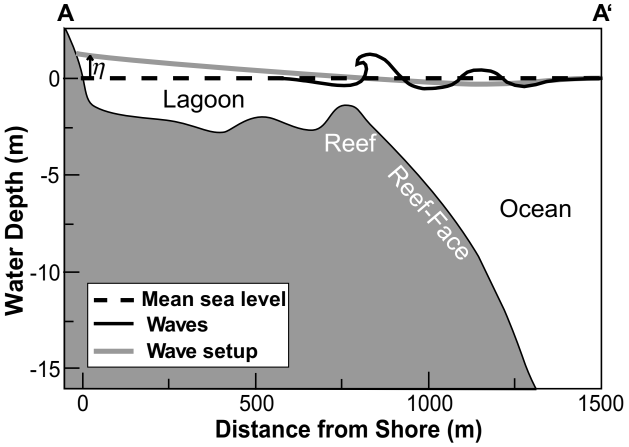

Figure 1 Cross-shore profile A—A′ illustrating the effect of wave breaking, with setdown occurring outside the breaker zone and wave setup (η) occurring inside the surf zone and at the coast.

is balanced by a sloping water level, causing setdown outside the breaker zone and setup inside the surf zone and at the coast (Longuet-Higgins and Stewart, 1963). Appreciable setup at the shoreline can last for several days, depending on the duration of energetic swell events. Studies relating wave setup and groundwater table variations are limited to beaches (e.g., Nielsen, 1989; Gourlay, 1992; Turner et al., 1997; Cartwright et al., 2004a; Li et al., 2004) or laboratory experiments (Cartwright et al., 2004b). Observations of groundwater responses to setup farther than 150 m from the coast are nonexistent.

Wave setup is significantly different from wave runup, with the latter occurring on a time scale of seconds. Wave runup on a sloping beach is characterized by instantaneous swash infiltration, resulting in immediate groundwater response (Li and Barry, 2000). The interaction between runup and the groundwater table in the littoral zone is well known (e.g., Hegge and Masselink, 1991). The amplitude becomes increasingly damped inland (Li et al., 1997) and is hardly detectable farther than tens of meters away from the shoreline (Cartwright et al., 2006).

Wave runup and setup can induce a hydraulic gradient that may change coastal groundwater flow, affect water quality (freshwater/saltwater interface), and contaminant transport in coastal areas (e.g., Turner et al., 1997; Nielsen, 1999). These dynamics can have important implications for the local population if it depends on coastal aquifers for their water supply (Cartwright et al., 2004a).

Ocean tides are commonly used to estimate aquifer parameters (e.g., Merritt, 2004; Trefry and Bekele, 2004). The harmonic signal decays as it propagates inland as a function of the aquifers hydraulic properties and distance to shore (Jacob, 1950; Ferris, 1951). However, wave setup has not been directly used to estimate hydraulic parameters, which are essential elements for analytical and numerical models used to manage groundwater availability and quality. Uncertainty in these parameters is reflected in erroneous model estimates and consequently leads to a potential mismanagement of drinking water supplies. Utilization of tides or setup to estimate aquifer parameters has an added advantage over aquifer tests by covering greater areas. In addition, the use is appealing due to the low costs and simple logistics involved. Wave buoy data are readily available, and reliable swell forecasts exist for seven days in advance through the National Oceanographic and Atmospheric Administration's (NOAA) WAVEWATCH-III model (Chao et al., 2003). A benefit of setup over tides is the deeper penetration into the aquifer associated with longer period oscillations.

The objectives of this study were to investigate the influence of wave setup on water-table elevations in central Maui, Hawaii, and to utilize setup to estimate hydraulic parameters. A simple numerical groundwater flow model was used to evaluate the accuracy of the estimated hydraulic parameters. The results were compared with aquifer parameters estimated for the same study area using aquifer tests (Rotzoll et al., 2007), specific-capacity (Rotzoll and El-Kadi, 2008), and tides (Rotzoll et al., 2008).

Study site

The island of Maui consists of two shield volcanoes. West Maui Volcano is composed mainly of thin-bedded shield-stage Wailuku Basalt. The west side of East Maui Volcano consists primarily of thin-bedded shield-stage Honomanu Basalt overlain by thicker and less permeable postshield-stage Kula Volcanics (Stearns and Macdonald, 1942). The study area encompasses the isthmus of central Maui, where lava flows of the two volcanoes coalesced (Fig. 2). The isthmus comprises Wailuku Basalt overlain by the two East Maui geologic units. Holocene marine and terrestrial sedimentary deposits cover the flank lavas. The sediments on the north side of central Maui consist of consolidated and well-sorted calcareous dune deposits (Stearns and Macdonald, 1942). The sediments are significantly less conductive than the basalts, and their thickness can reach 25 m at the coast, where they can form a low-permeability capping unit.

Groundwater in the study area occurs in an unconfined aquifer, in the form of a basal freshwater lens (Takasaki, 1972). The depth of the aquifer is not physically defined due to missing geologic information. A reasonable aquifer depth is 1800 m below mean sea level, which coincides with a seismic velocity unconformity detected on Oahu (Furumoto et al., 1970). Rotzoll et al. (2007) analyzed 238 aquifer tests and estimated a mean hydraulic conductivity of 310 m/d for the Honomanu/Kula basalts. Using an empirical relationship between hydraulic conductivity and specific-capacity, Rotzoll and El-Kadi (2008) estimated a mean hydraulic conductivity of 423 m/d for 218 wells in Maui's dike-free flank lavas. Rotzoll et al. (2008) used tidal responses and estimated a mean hydraulic diffusivity of 2.3×10^7 m^2/d. A specific yield value of 0.04 is commonly used in numerical models for basalts in Hawaii (e.g., Oki, 2005).

The coastal regions on the north side of central Maui are situated in the center of a V-shaped embayment (Fig. 2a). The wave heights on north-facing shorelines in Hawaii are characterized by a quasi-normal distribution with a maximum in January and a minimum in July. From December to February the large swells experience a shift toward more west-northwesterly directions, due to the southerly migration of the north Pacific storm track (Caldwell, 2005). The coastal bathymetry includes a 1- to 2-km-wide shelf with a