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NUMERICAL MODELING OF ATOLL ISLAND HYDROGEOLOGY

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ABSTRACT

The freshwater lens of an atoll island is an extremely fragile resource for the island population. The extent to which climatic and geologic factors govern the thickness of the freshwater lens of atoll islands is demonstrated in this study by revisiting the conceptual model of atoll island hydrogeology presented by Ayers and Vacher (1986). The numerical modeling code SUTRA was employed to quantify the relationships between the thickness of the freshwater lens and the principal environmental factors which govern it. Steady-state simulation results show that the thickness of the lens is influenced by the recharge rate, island width, hydraulic conductivity of the Holocene deposits, and depth to the Thurber Discontinuity. Transient simulation results show that approximately one and a half years are required for a full recovery of the lens from a six-month drought.
The position of the island relative to the prevailing winds also has a strong influence on the development of the hydraulic conductivity of the Holocene aquifer. Comparisons between numerical simulations and observed field values demonstrate that, in a very general sense, the hydraulic conductivity of the Holocene aquifer on leeward and windward islands on an atoll is 50 m day^{-1} and 400 m day^{-1}, respectively.

INTRODUCTION

Atolls have been a subject of scientific interest for centuries (Vacher, 1997). These unique geologic features are generally composed of a somewhat-circular chain of small, coral islands, enclosing or nearly enclosing a shallow lagoon (Neuendorf et al., 2005) (Figure 1).

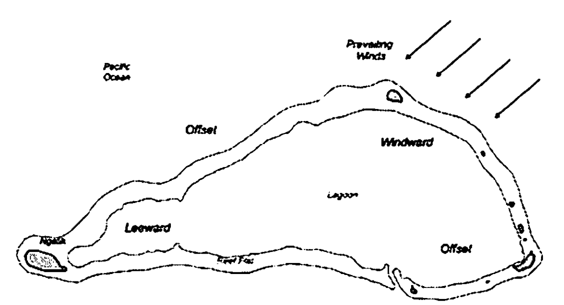

Figure 1. Map of Sapwuahfik Atoll, Pohnpei State, Federated States of Micronesia, showing prevailing winds and the windward, leeward, and offset sections on the atoll.

Water for drinking and cooking for most atolls in the Federated States of Micronesia is normally supplied from roof catchments or coconut juice, while water for bathing and washing clothes is supplied from hand-dug wells (Stephenson, 1984; Bailey, 2008). During time of drought, however, groundwater may be used for all domestic purposes (Arnow, 1954). Information regarding groundwater, however, is not readily available for the vast majority of atoll islands around the world.

The general pattern for atoll subsurface geology is a surficial, Holocene-age aquifer resting upon a Pleistocene-age aquifer. For hydrologic purposes this pattern has been described as the dual-aquifer conceptual model of atoll island hydrogeology (Ayers and Vacher, 1986) (Figure 2). The hydraulic con-ductivity of the Pleistocene aquifer has been estimated to be one to two orders of magnitude more than that of the Holocene aquifer (Hunt and Peterson, 1980), and limits the growth of the freshwater lens at or near the base of the Holocene aquifer (Falkland, 1994; Peterson, 1997). This boundary has been termed as the "Thurber Discontinuity" (Vacher, 1997), a solution discontinuity (Thurber et al., 1965) located approximately 15-25 m below sea level (Wheatcraft and Buddemeier, 1981; Hamlin and Anthony, 1987). Groundwater movement is also affected by the reef flat plate, a semi-permeable slab of reef rock which acts as a confining layer to the Holocene aquifer, forcing freshwater to discharge from fractures in the plate or at the reef (Buddemeier and Holladay, 1977; Ayers and Vacher, 1986).

The hydraulic conductivity of the Holocene aquifer depends on the position of the island in reference to the prevailing winds (Anthony, 1997; Spennemann, 2006). Islands on the leeward portion of the atoll tend to be larger in size and possess finer subsurface deposits and lower permeabilities than those exposed to the prevailing winds on the windward side. This low permeability enables the development of much thicker lenses than found on windward islands (Anthony, 1997).

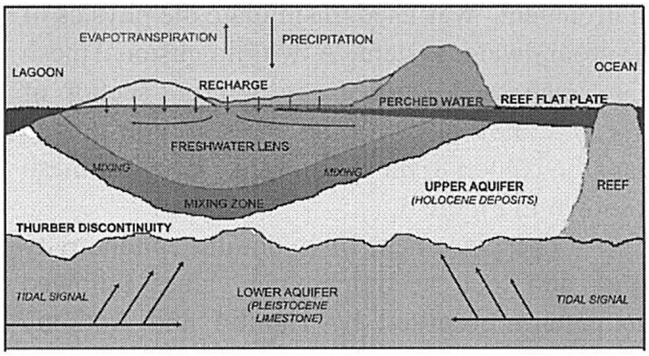

Figure 2. Conceptual model of the hydrogeology of an atoll island, after Ayers and Vacher (1986)

The purpose of this study was to investigate and quantify the effects of the governing climatic and geologic features on the freshwater lens of atoll islands. Features of the dual-aquifer conceptual model of atoll island hydrogeology have been employed in numerical modeling studies (Herman and Wheatcraft, 1984; Hogan, 1988; Griggs, 1989; Oberdorfer et al., 1990; Underwood, 1990; Underwood et al., 1992; Gingerich, 1992; Griggs and Peterson, 1993; Peterson and Gingerich, 1995). However, the full conceptual model has not been implemented numerically until now. Steady-state simulations investigate the changes in lens thickness due to average annual recharge rate, island width, Thurber Disconti-nuity depth, Holocene aquifer hydraulic conductivity, and presence or absence of the reef flat plate. Transient simulations, using a daily recharge series, investigate the effects of El Nino and a washover event on the behavior, thickness, and recovery of the freshwater lens.

NUMERICAL MODELING

Mesh Design and Input Parameters

The USGS numerical model SUTRA (Voss, 2002), which simulates groundwater flow and solute transport in a fluid density-dependent environment, was used to simulate the physics of the groundwater system. A two-dimensional mesh was constructed to represent the cross-section of a generic atoll island. The cross-section ranged from the lagoon to the ocean side. A typical mesh is shown in Figure 3.

The placement of hydraulic conductivity zones and their accompanying values followed the pattern observed by Hamlin and Anthony (1987) on Laura Island, Majuro Atoll, where the Holocene aquifer was divided into two zones of slightly differing permeability (see Figure 3B). Eight meshes were used, ranging in island width from 150 m to 1100 m. Fluid pressure and fluid source boundaries were placed as shown in Figure 3. Water flowing inward at pressure boundaries was given a salt concentration of 0.0357 kg NaCl / kg water. Incoming rain water at the fluid source boundary was given a salt concentration of 2.0×10^{-5} kg NaCl / kg water (Anthony, 1987). For steady-state simulations the annual rate of recharge was taken to be half of the annual rainfall (Hamlin and Anthony, 1987). The bottom of the mesh and the boundary simulating the limit of the lagoon were assigned as no-flow boundaries. So-lute mass concentration for potable water was

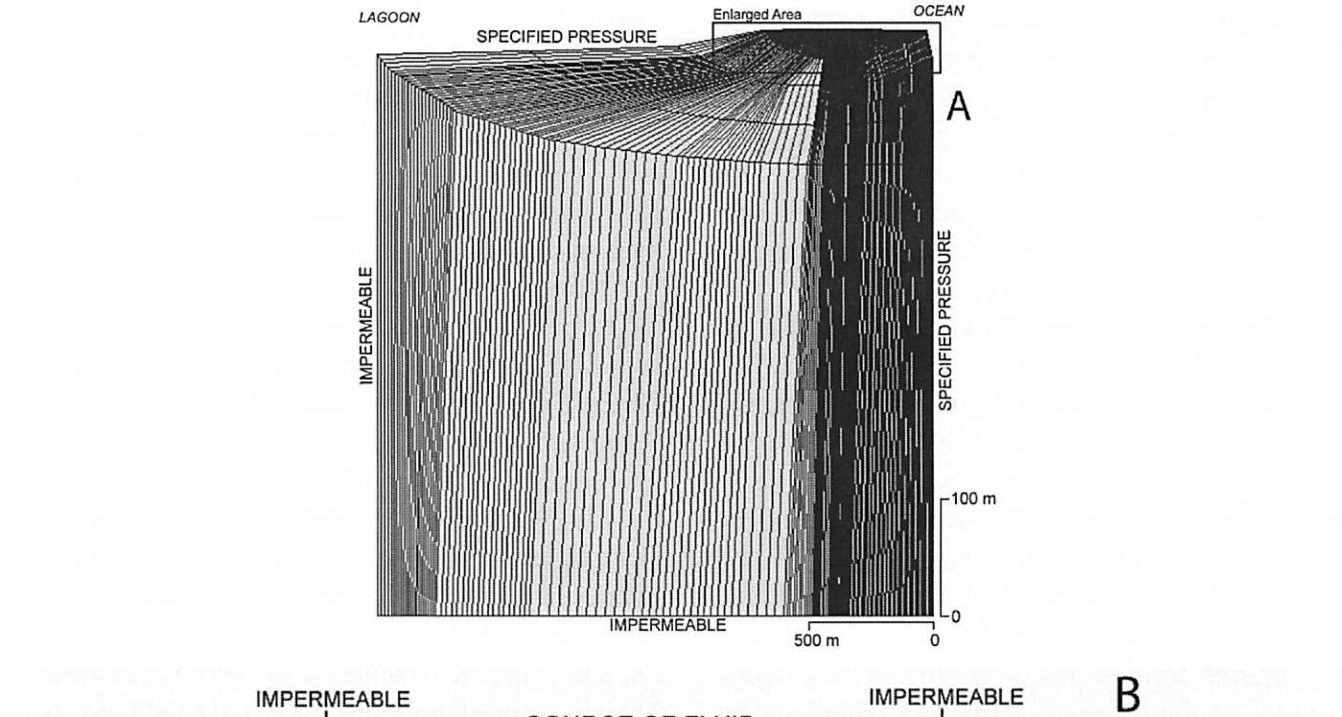

Figure 3. (A) Mesh constructed for SUTRA simulations, with boundary conditions, and (B) close-up of shallow island subsurface, showing the geologic units.

designated as 0.00089 kg salt / kg water, which corres-ponds to a chloride (Cl^-) concentration of 500 mg L^{-1}. Each simulation was run for seven year periods at hourly time-steps to achieve a steady-state condition.

Steady-State Simulations and Results

Four steady-state baseline sensitivity test series were run in order to quantify the influence of recharge, hydraulic conductivity, depth to the Thurber Discontinuity, and the presence of the reef flat plate on the maximum lens thickness. Recharge was varied between 1.25 and 2.75 m yr^{-1}, hydraulic conductivity of the Holocene deposits was varied between 25 and 500 m day^{-1}, and the depth to the Thurber Discontinuity was varied between 8 and 18 meters below MSL. The test series for the reef flat plate compared simulations for each island width with and without the plate.

Results from the sensitivity test series (Figure 4) show an overall increase in lens thickness (Z Max) with an increase in recharge rate (Figure 4A), Thurber Discontinuity depth, and island width, and a decrease in lens thickness with an increase in Holocene aquifer hydraulic conductivity (Figure 4B). The increase in lens thickness is always limited at the Thurber Discontinuity. The presence of the reef flat plate slightly thickens the lens.

Figure 5 presents a plot of the results from the hydraulic conductivity numerical simulation series super-imposed onthe observed lens thicknesses of leeward atoll islands (gray triangles) and atoll wind-ward islands (white squares). When the hydraulic conductivity in the numerical simulations was set to 50 m day^{-1}, the resulting lens thickness plotted along the trend of the observed leeward island lens thicknesses, and when the hydraulic conductivity in the simulations was set to 400 m day^{-1}, the resulting lens thickness plotted along the trend of the observed windward island lens thicknesses. This led to the general conclusion that the hydraulic conductivity of the Holocene sediments on leeward and windward islands is 50 m day^{-1} and 400 m day^{-1}, respectively (Figure 5) (Bailey, 2008).

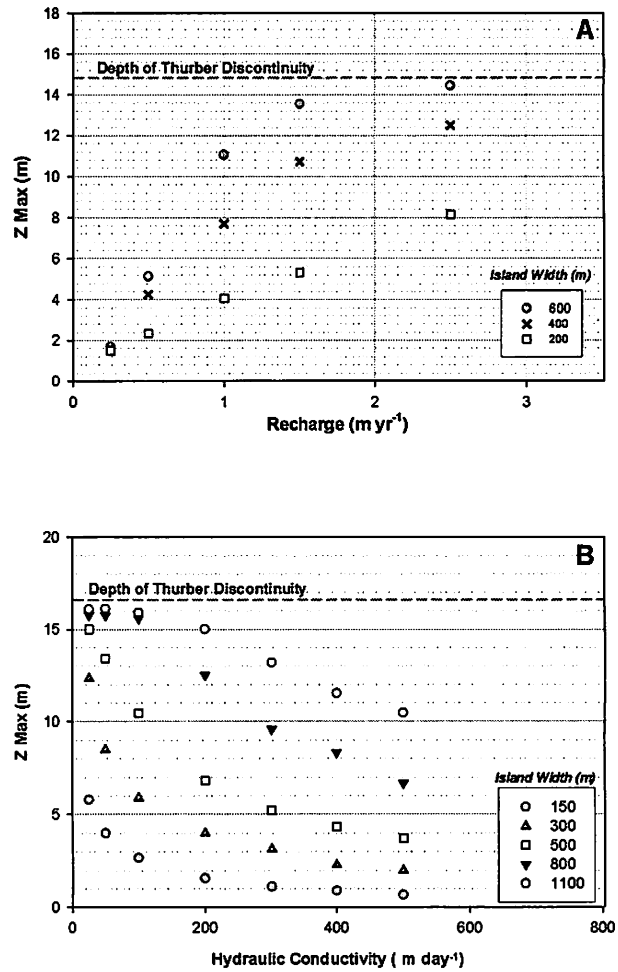

Figure 4. Results for the (A) Recharge, with the lens thickness designated by Z Max, and (B) Hydraulic Conductivity test series.

Transient Simulations and Results

El Nino Event

Simulations were run using time-varying boundary conditions in order to quantify the effects of an El Nino event and a washover event on the freshwater lens.

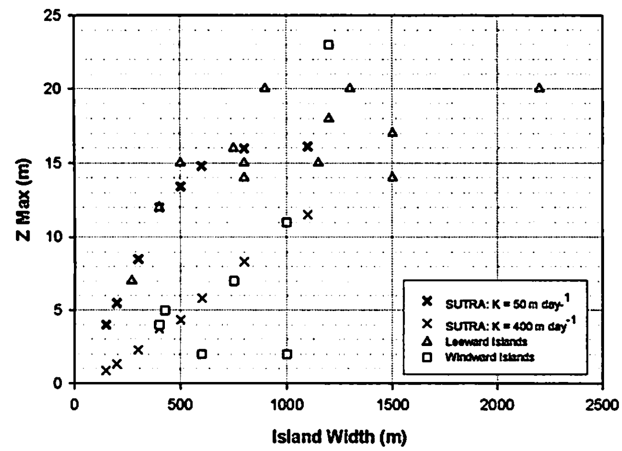

Figure 5. Comparison between observed lens thicknesses on leeward and windward atoll islands and the corresponding SUTRA numerical simulation results.

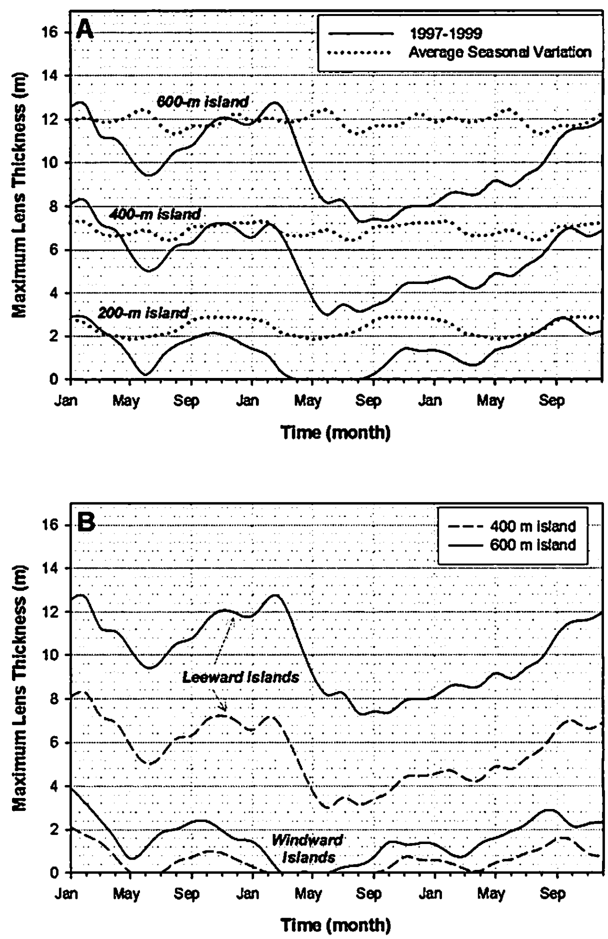

Figure 6. Results of El Nino simulations, showing (A) fluctuation of lens thickness during January 1997 to December 1999 for island widths of 200 m, 400 m, and 600 m, compared with the fluctuation of the lens thickness during a non-El Nino year, and (B) comparison of lens thickness fluctuation between lee-ward and windward islands for the same range of years.

An El Nino event was simulated using the weather data from island regions in the Federated States of Micronesia and the recharge model from Falkland (1994). Daily rainfall data for the years 1997-1999 from Yap and Pohnpei islands were fed into the recharge model to create daily recharge series, which were then used as input for the numerical model (Bailey, 2008). Hourly tidal data was used as input at the fluid pressure boundaries. Simulations were run for island widths (200 m, 400 m, and 600 m), rain-fall rates (Yap and Pohnpei data), and location of the island (leeward or windward side of the atoll). Simulations for leeward and windward islands used hydraulic conductivities of 50 m day^{-1} and 400 m day^{-1}, respectively (Bailey, 2008).

Results of the simulations (Figure 6) show the lens thickness decreasing rapidly during the drought occurring during the first half of 1998, followed by a steady recovery. Larger islands sustain a thicker lens (Figure 6A), as do leeward islands (Figure 6B). The lens on small, windward islands is completely depleted during the drought period. In general, approximately one and a half years are required for the recovery of the lens to p-re-drought conditions.

Washover Event

A washover event, when waves ot surf wash over parts of the island, is another extreme weather phenomenon that strongly affects the freshwater lens. Washover events occur periodically on small, low-lying islands (Lessa, 1964) as the high surf during tropical storms and typhoons is carried across the island's surface, inundating the interior of the island and leaving standing sea water, which subsequently infiltrates down through the soil and contaminates the freshwater lens.

Simulations were run to analyze the recovery time of the freshwater lens from a washover event. Real-time hydrologic data for a washover event is at present not available. As such, these scenarios are thus treated hypothetically. Test series were run in order to investigate the effect of (1) washover depth, ranging from 0.25 m to 1.50 m (2) washover duration, ranging from 12 hours to 48 hours (3) recharge rate, using Yap and Pohnpei rainfall data, and (4) hydraulic conductivity of the Holocene deposits, ranging from 50 m day^{-1} to 400 m day^{-1}, on the recovery of the lens. The maximum thickness of the fresh-water lens was monitored throughout each simulation to observe the progress of the lens. Unless varied in a sensitivity test series, the duration and depth of the washover was held at 24 hours and 0.50 meters, respectively, island width was 400 m, Holocene aquifer hydraulic conductivity was held at 50 m day^{-1}, and the reef flat was present. The recovery of the lens was simulated using the daily rainfall and hourly tide data from 2003-2005.

The most striking general outcome of the simulations was the influence of the reef flat plate. The portion of the aquifer overlain by the plate, protected from the infiltrating seawater, maintained a nucleus of freshwater throughout the simulation, while the unconfined portion of the aquifer was quickly contaminated with infiltrating seawater (Figure 7).

The results of the duration sensitivity test series (Figure 8A) show that there is almost no differ-ence in lens recovery time between an event wherein the washover of the island lasted for 12 hours ver-sus one that lasted for 48 hours, with the 48-hour event lagging a month or two behind the 12-hour event in recovery time. It should be noted that recovery of the lens is highly dependent on the rainfall patterns in the months following the washover event. Hence, the lens thickness in-

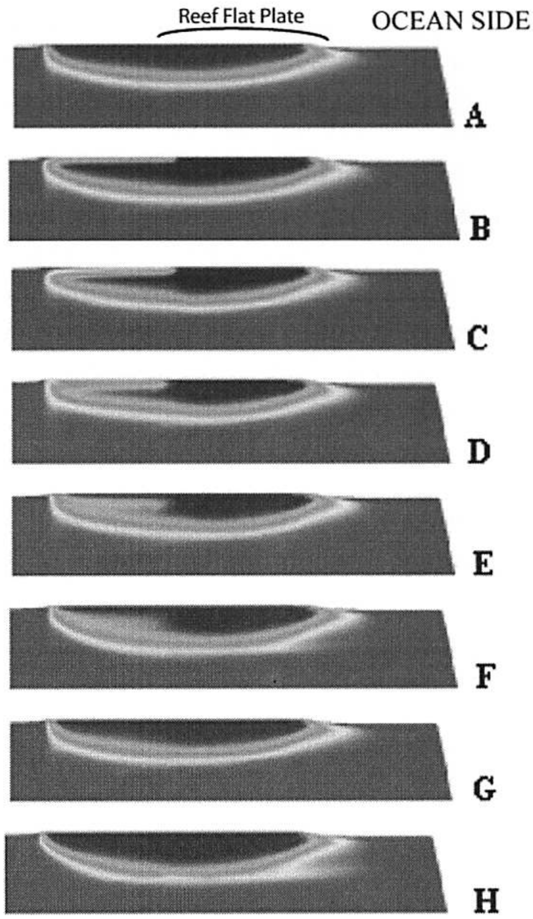

Figure 7. Contamination and recovery of the freshwate r lens from a 48-hour washover event, at (A) initial conditions, (B) 16 hours, (C) 48 hours, (D) 1 month, (E) 2 months, (F) 4 months, (G) 1 year, (H) and 1 ½ years. Dark gray represents water with a chloride concentration of less than 500 mg L^{-1}, which grades into seawater. The portion of the lens on the ocean side, underneath the reef flat plate, is protected from contamination.

creases (due to high monthly rainfall rates) during months 4 and 5, and then decreases (due to low monthly rainfall rates) during month 6 to 8 (Figure 8A). The washover depth test series (Figure 8B) shows that there is a threshold at which the subsurface interior of the island becomes contaminated with seawater and the lens must go through the full recovery process. For depths of 0.25 meters and less, there is not enough mass of infiltrating seawater to sustain contamination before it is flushed out to the seacoast by the infiltrating freshwater. This aspect of washover events needs further analysis. Recharge rate has a large influence (Fig-ure 8C), with the higher recharge rate flushing out the seawater more quickly. The hydraulic conductivi-ty of the Holocene aquifer also has an impact (Figure 8D), with low-hydraulic conductivity islands hav-ing a quick initial recovery time due to the rapid flushing of the aquifer.

CONCLUSIONS

Numerical investigations of atoll island hydrogeology, through implementation of the dual-aquifer conceptual model of Ayers and Vacher (1986) quantifies the influence of the governing climatic and geologic factors and demonstrates the fragility of the lens. This fragility is accentuated for small, windward islands, but also becomes important for all atoll islands during periods of drought or the af-termath of extreme weather events, such as a washover event.

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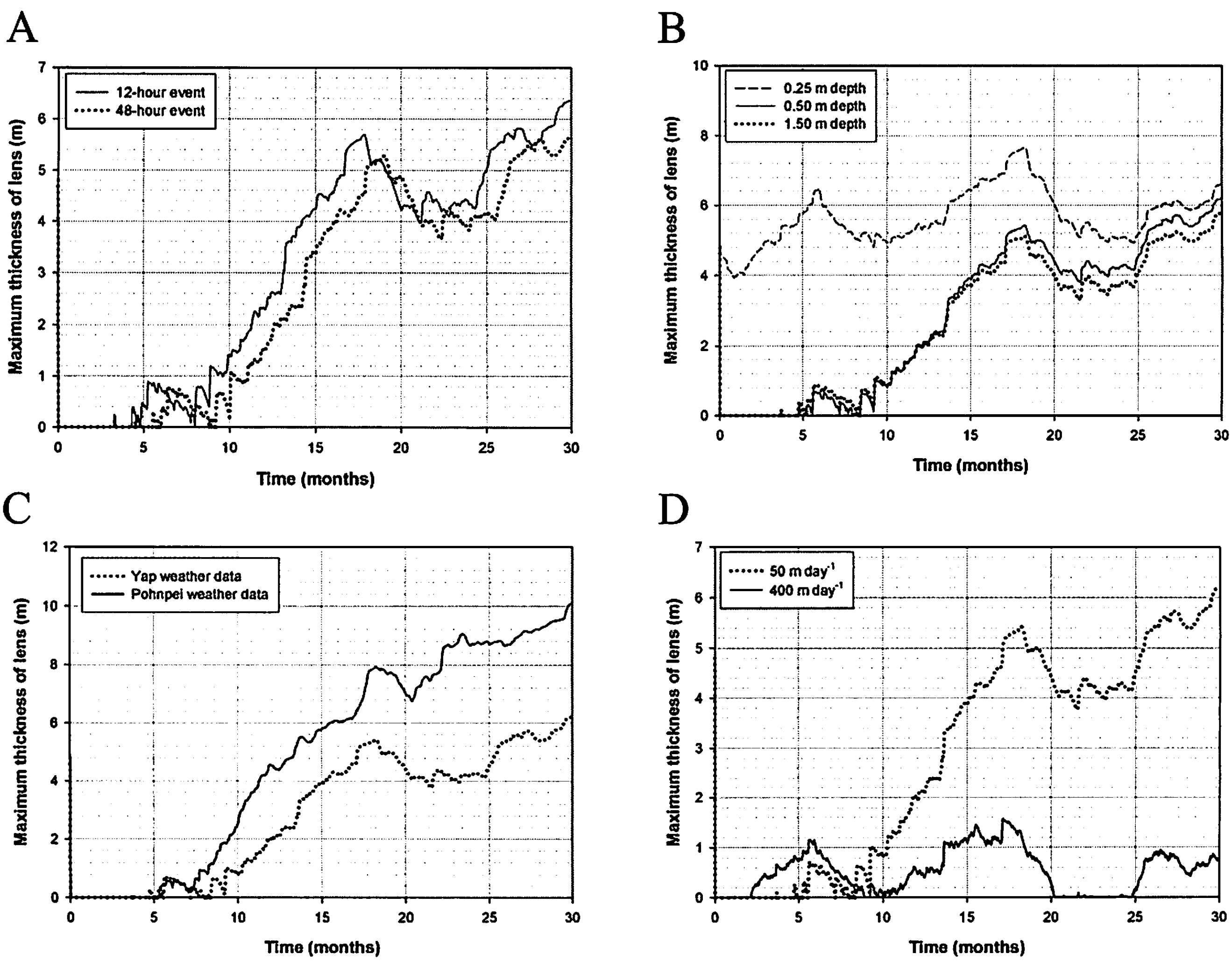

Figure 8. Washover simulation test series. Results for (A) Duration of washover event, (B) Depth of washover, (C) Recharge rate, and (D) Hydraulic conductivity of the Holocene aquifer.

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