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Numerical modelling of vertically extensive groundwater bodies in Maui, Hawaii: an alternative to perched aquifers

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Abstract Groundwater in East Maui, Hawaii is traditionally described as a series of discrete aquifers perched on low-permeability units underlain by a basal lens with heads of about 2–3 m. An alternative concept, a fully saturated aquifer to as much as 1400 m elevation, was investigated using a numerical model with various horizontal hydraulic conductivity values and anisotropy ratios. Results indicate that horizontal hydraulic conductivity values between about 0.08 and 1.0 m per day and anisotropy ratios between 1:1 and 100:1 will produce simulated water tables that match observed water tables at 400–1400 m elevation. These values of hydraulic conductivity are consistent with available field data for hydraulic conductivity.

Simulación numérica de cuerpos de agua subterránea con una extensión significativa vertical, Isla de Maui, Hawaii: alternativa a acuíeros colgantes

Resumen Tradicionalmente la existencia de agua subterránea en la parte oriental de la isla de Maui, Hawaii, se ha descrito como una serie de acuíferos colgantes de extensión limitada separados entre sí por estratas de baja permeabilidad sobrepuestos a un lente de agua basal con una carga piezométrica de 2–3 m. Se presenta un modelo conceptual de un acuífero saturado en su totalidad vertical hasta una altitud de 1400 m. El modelo conceptual se evaluó mediante un análisis numérico variando valores de conductividad hidraúlica y de anisotropía. Los resultados obtenidos demuestran que valores de conductividad hidraúlica entre 0.08 a 1.0 m por día con una razón de anisotropía de 1:1 y 100:1 reprodujeron los niveles freáticos entre los 400–1400 m de altitud. Los valores de conductividad hidraúlica usados en el modelo son comparables con los datos de campo.

INTRODUCTION

The windward slope of East Maui Volcano, Hawaii extends from the coast of the island to the northern rim of Haleakala at an elevation of more than 2440 m a.m.s.l. (Fig. 1). The volcano is composed mainly of numerous basaltic lava flows ranging from a few metres to a few hundred metres thick. The thick basaltic sequence is composed of aa flows, clinker beds, pahoehoe flows, ash layers and intrusive bodies, and is cut by many deeply incised valleys with alluvial deposits. Streams carry runoff and baseflow from drainage basins that receive as much as 7000 mm year^{-1} of rainfall (Fig. 1). This paper relies mainly on data for the Hanawi Stream basin which is a typical East Maui drainage basin and has been studied in detail.

Stearns & Macdonald (1942) state that groundwater in East Maui occurs in a series of perched aquifers in which intrusive rocks, ash beds, soil layers and

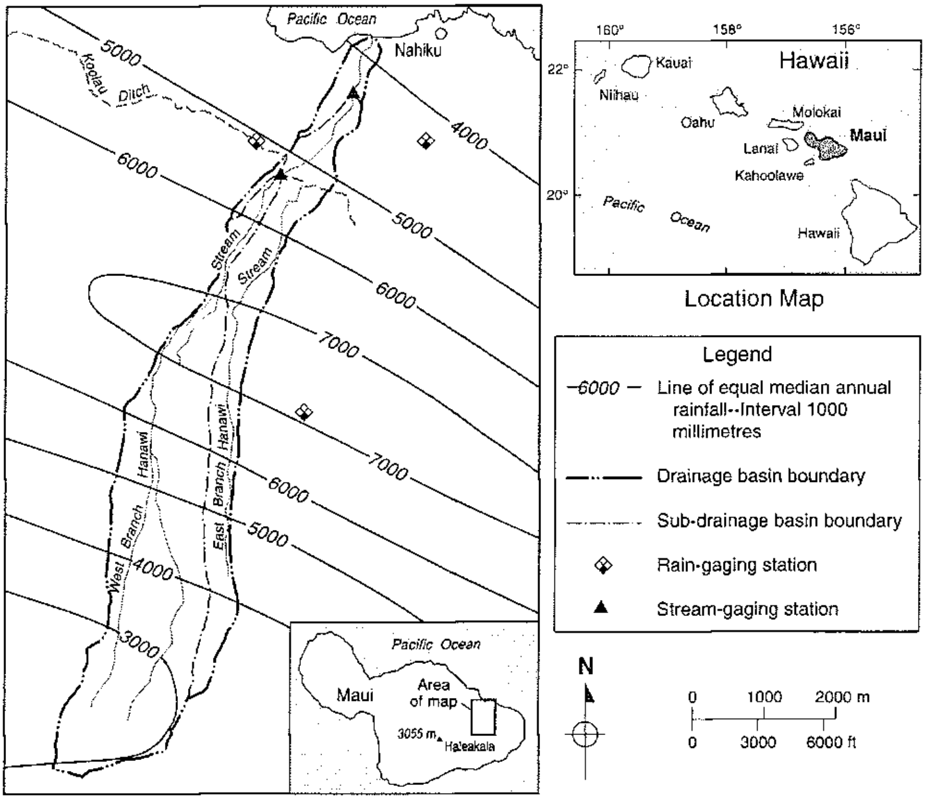

Fig. 1 Location of the study area and annual rainfall distribution near Hanawi Stream drainage basin, East Maui, Hawaii.

alluvium act as perching units and are underlain by a basal lens in which heads are from 2 to 3 m a.m.s.l. They report groundwater levels as high as 430 m a.m.s.l. in the perched units on the basis of measurements made in test borings drilled throughout the area. They also refer to results of unpublished seepage studies from streams in the area which indicate that groundwater may discharge at elevations as high as 1400 m a.m.s.l. (Stearns & Macdonald, 1942, Fig. 25). Large springs, one of which discharges as much as 294 000 m^3 day^{-1}, issue from some of the more permeable units (usually aa clinker layers) in the sequence. Test borings drilled into some of these units revealed the presence of artesian conditions.

This study provides an alternative explanation for the occurrence of high-level groundwater discharge in East Maui. Rather than perched aquifers, the occurrence of high-level groundwater can be explained by a single extensive groundwater body which fully saturates the aquifer from below sea level to an elevation exceeding 1400 m. This alternative is investigated with a numerical groundwater flow model which uses hydrologic properties consistent with the field data for the area. The numerical model is a generalized representation of the flow system which assumes a homogenous aquifer having a single value of hydraulic conductivity for the entire thickness of the aquifer. The implications of this simplifying assumption are discussed later in this paper.

NUMERICAL SIMULATION OF THE AQUIFER

Groundwater flow in the aquifer was simulated with the quasi-three-dimensional groundwater model SHARP (Essaid, 1990), a finite difference numerical model which simulates an aquifer containing freshwater and salt water. The two waters are assumed to be separated by a sharp interface, the location of which approximates the midpoint of the transition zone between freshwater and salt water in the aquifer. The position of the interface is based on an equal balance of pressure between freshwater and salt water on either side of the interface. SHARP simulates water levels and includes the effects of both freshwater and salt water flow dynamics. The groundwater model simulates a simple flow system with recharge entering the top of the system. In this system, a freshwater lens is created. Where heads are higher than the land surface, a portion of groundwater discharges as baseflow into a stream valley. The remaining groundwater discharges into the ocean. The height of the water table is controlled mainly by the amount of recharge, the hydraulic conductivity of the aquifer and the topography. Because the amount of recharge and the topography are kept constant in the model, the effects of hydraulic conductivity on the height of the water table are easily investigated.

Description of the groundwater model

The grid used to represent a vertical section of the aquifer beneath East Maui covers an area 15 050 m long by 641 m wide and extends from an elevation of –900 m to the ground surface at a maximum elevation of 1800 m (Fig. 2). The homogeneous four-layer model was extended into the ocean far enough (4000 m) so that a constant-head boundary at the oceanward edge of the grid would not affect the flow dynamics in the aquifer. The top layer, which is unconfined, has a variable thickness to match the topographic profile of the mountain flank along Hanawi Stream (Fig. 2) and the other three layers have a constant thickness. Discharge of groundwater along the shoreline of the island is simulated with a head-dependent flux boundary. The ocean discharge is controlled by the difference between the freshwater head in the aquifer and the equivalent freshwater head at the sea floor, as well as the vertical hydraulic conductivity of the aquifer. The equivalent freshwater head at the sea floor was determined from the thickness of sea water overlying the sea floor based on the bathymetric profile offshore of the town of Nahiku (Fig. 2).

A no-flow boundary at the base of the model represents the depth where the aquifer is assumed to have a sufficiently low permeability and porosity such that groundwater flow is insignificant below this boundary. The average depth below ground surface of the assumed no-flow boundary is 1900 m. There are no data documenting aquifer properties below sea level in this system but the extreme pressure of the overburden probably holds fractures closed at these depths. Studies of similar thick basaltic sequences on Kilauea Volcano using geophysical techniques and core samples have shown that porosities may be nearly zero at depths of 2000 m or more (Kauahikaua, 1993).

In plan view (Fig. 2), the active part of the grid is three rows wide with the centre row representing a stream valley (30 m wide) and the two outer rows (each

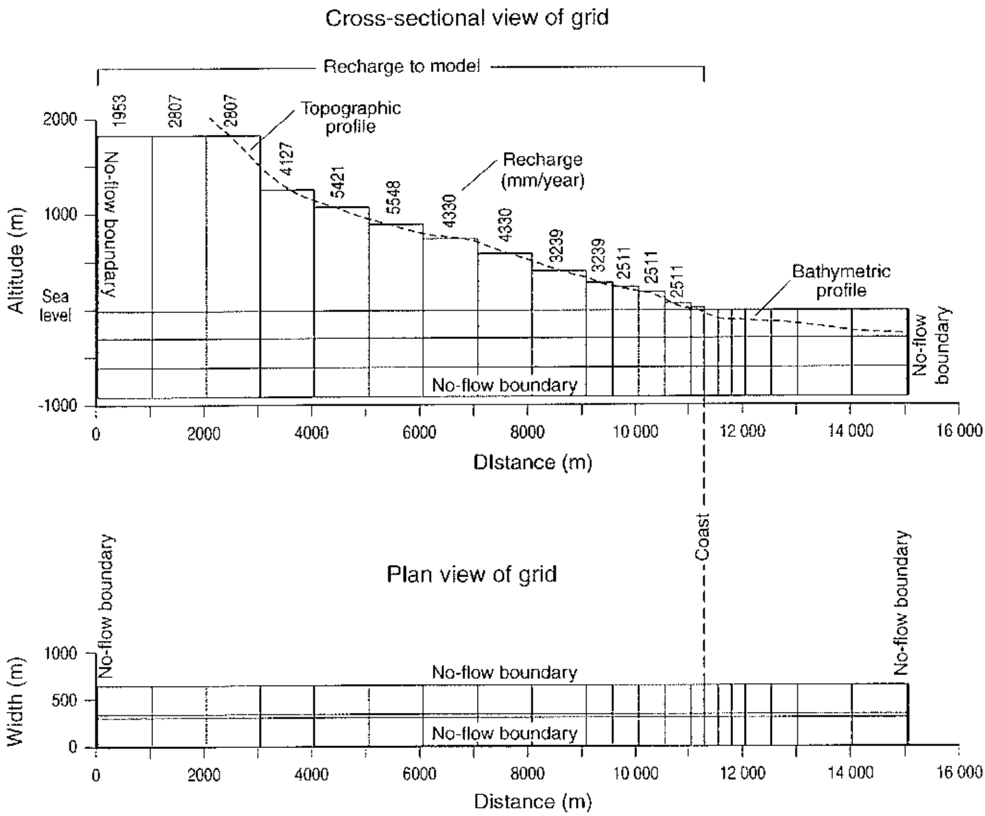

Fig. 2 Grid and boundary conditions used in aquifer simulations, East Maui, Hawaii.

305 m wide) representing the areas between the stream valley and the drainage basin boundaries. Some stream cells also were designated as head-dependent flux boundaries with the overlying head maintained at the land surface elevation.

Recharge to the model was based on a geographic information system water budget calculated for the Hanawi Stream drainage basin (P. J. Shade, USGS written communication, 1996). Recharge varied with elevation, precipitation (Fig. 1) and soil type, and ranged from 1950 to 5550 mm year^{-1}. The values of horizontal hydraulic conductivity (K_h) used in the aquifer simulations ranged from 0.03 to 0.91 m day^{-1} and the aquifer was considered homogeneous. Vertical hydraulic conductivity values (K_v) ranged from 0.0015 to 0.91 m day^{-1} and anisotropy ratios (K_h:K_v) ranged between 1:1 and 100:1 (Table 1). In SHARP, the vertical hydraulic conductivity is controlled with a term which describes the hydraulic connection between adjacent layers. For homogeneous layers, the hydraulic connection is defined as $K_v\, m^{-1}$, with m being the distance from the midpoint of the underlying cell to the midpoint of the overlying cell. Because the thickness of the top layer varied with the height of the water table, the hydraulic connection between this layer and the underlying layer was calculated after each simulation and values were adjusted iteratively until subsequent changes were insignificant to the results. Usually only one or two iterations were needed to reach an acceptable solution.

Table 1 Results of East Maui, Hawaii aquifer simulations.

Simulation number	Horizontal hydraulic conductivity, K_h, (m day^{-1})	Vertical hydraulic conductivity, K_v (m day^{-1})	Anisotropy ratio, K_h:K_v	Elevation, h, where simulated stream discharge begins (m)
1	0.03	0.03	1:1	1738
2	0.15	0.0015	100:1	1227
3	0.15	0.015	10:1	1188
4	0.15	0.15	1:1	1172
5	0.30	0.003	100:1	1012
6	0.30	0.03	10:1	877
7	0.30	0.091	3.3:1	863
8	0.30	0.30	1:1	856
9	0.61	0.0061	100:1	707
10	0.61	0.061	10:1	521
11	0.61	0.15	4:1	508
12	0.61	0.30	2:1	395
13	0.61	0.61	1:1	390
14	0.91	0.0091	100:1	517
15	0.91	0.091	10:1	283
16	0.91	0.91	1:1	131

Along the shoreline and at some of the stream cells, groundwater moves upward from the aquifer to discharge into the ocean or stream. The vertical hydraulic conductivity of the aquifer and any ocean bottom or streambed sediments resist this upward movement. Discharge of groundwater from the aquifer is proportional to the effective vertical hydraulic conductivity of both the aquifer and the sediments (K') divided by the thickness of the aquifer and sediments through which discharge occurs (m'). The ratio of $K'm'^{-1}$ is referred to as the hydraulic connection between the aquifer and the ocean or stream. Because of a lack of information about the hydrologic properties of streambed or ocean bottom sediments, the hydraulic connection was based only on the vertical conductivity of the aquifer; additional effects of the sediments were not incorporated into the model. Therefore, the thickness is just equal to half of the thickness of the upper layer.

Results of simulations

The primary results obtained from the model simulations were the positions of the water table and the locations of the highest elevation (h) where groundwater began to discharge into the stream using the different combinations of K_h and K_v listed in Table 1. Figure 3 shows the model-calculated water table position for five different simulations in which K_h ranged from 0.03 to 0.91 m day^{-1} while the anisotropy ratio was maintained at 1:1. The shaded area in Fig. 3 indicates the range of water levels (430–1400 m a.m.s.l.) which has been observed or estimated from test borings and stream measurements in East Maui. Horizontal hydraulic conductivity values using 0.15 or 0.3 m day^{-1} in an isotropic aquifer produced simulated water levels which

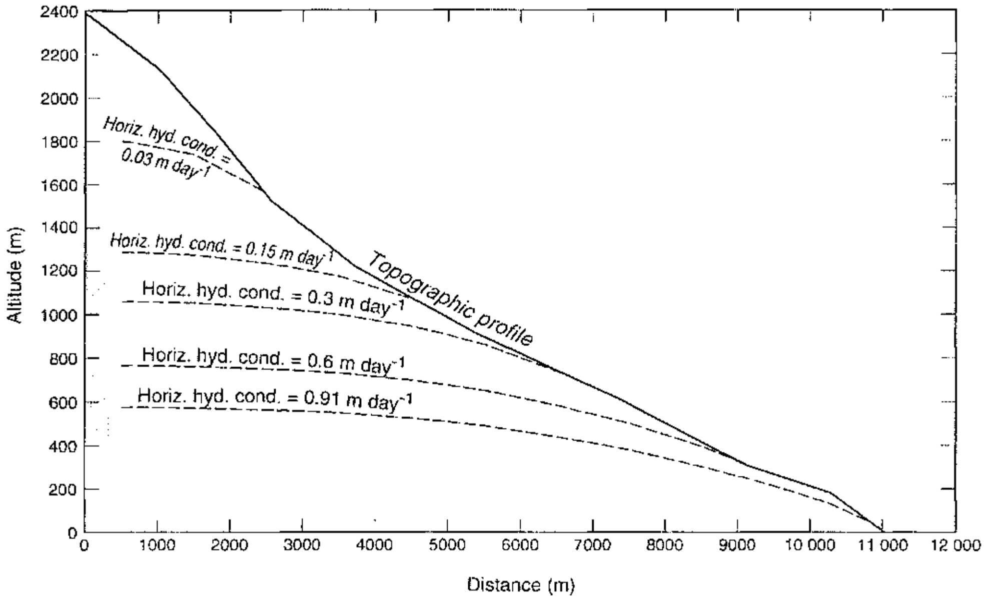

Fig. 3 Model-calculated water table positions for simulations using various values of horizontal hydraulic conductivity in an isotropic aquifer, East Maui, Hawaii. The shaded area represents the range in elevation where water is observed to discharge to the stream.

allow groundwater to discharge to the stream in this elevation range which is consistent with values reported by Meyer (William Meyer, USGS written communication, 1996) in the range of 0.1–0.2 m day^{-1}, based on a single well aquifer test performed in the Nahiku area.

The altitude of the simulated h ranged from 131 m a.m.s.l. when K_h was 0.91 m day^{-1} to 1738 m a.m.s.l. when K_h was lowered to 0.03 m day^{-1}. The increase in simulated h is a result of the increased resistance to groundwater flow caused by successively lower values of horizontal hydraulic conductivity. As the hydraulic conductivity decreased, more head was needed to push water through the flow system, hence higher water levels developed.

Field observations of the lava flows that make up the aquifer in East Maui show that the flows average about 6 m thick near the volcano summit and 15 m thick near the periphery, but flows 60 m thick are not rare (Stearns & Macdonald, 1942). Hunt (1996) states that thicker massive flows tend to diminish overall permeability, but probably more so in the vertical dimension, increasing the horizontal to vertical anisotropy. Hunt (1996) discusses several estimates of anisotropy for Hawaiian lava aquifers which range from 3:1 to 200:1. Anisotropy was introduced into the model by systematically lowering the value of vertical hydraulic conductivity for each given value of horizontal hydraulic conductivity. As the vertical hydraulic conductivity was reduced (i.e. the anisotropy ratio was raised), the resistance to vertical flow was increased and the elevation of the simulated water table rose. Figure 4 is a plot of the 16 different simulations including the elevation where groundwater begins to discharge into the stream. The shaded region includes the various combinations of K_h and K_v which produce simulated water levels in the range of observed water levels in

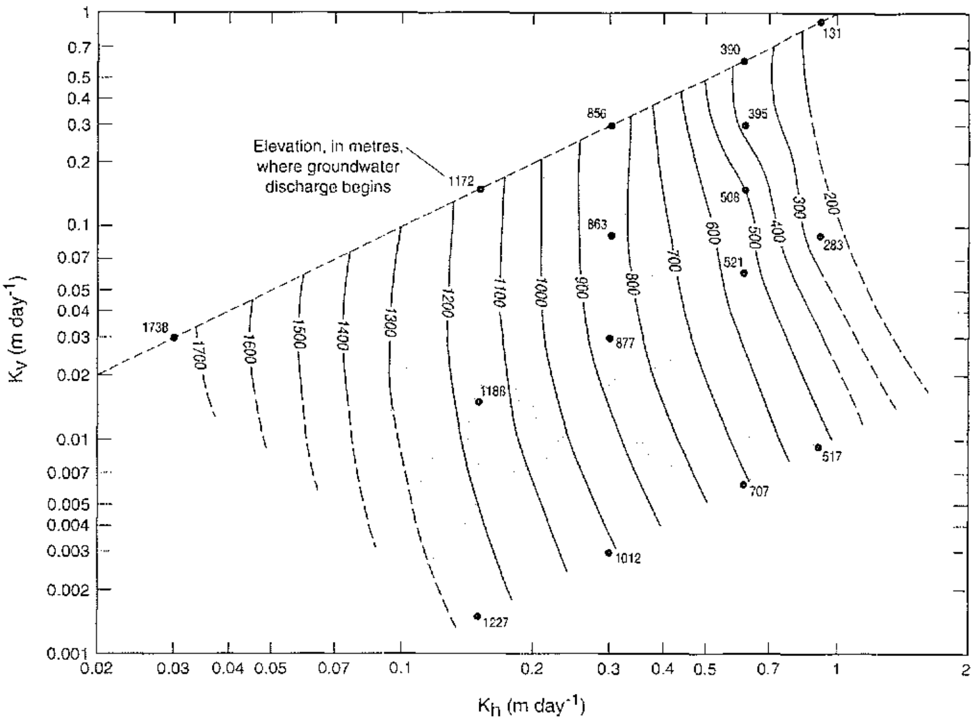

Fig. 4 Contour plot of model-calculated lowest elevation (h) where groundwater discharge begins for 16 simulations using different combinations of K_h and K_v, East Maui, Hawaii. Contour line spacing is 100 m, dashed where approximate. The shaded area represents the range in elevation where water is observed to discharge to the stream.

East Maui. This plot demonstrates the non-uniqueness of the model but it also defines a relatively narrow range of hydraulic conductivity values needed to reproduce observed field conditions. The irregularity in the smooth pattern in the upper right portion of the plot is attributed to the effects of coarse grid discretization and uneven topography at about 500 m altitude.

This simple numerical model simulates a flow system which discharges groundwater from a homogeneous aquifer to a stream valley along the entire length of the stream below the initial discharge elevation. Because no inhomogeneity was incorporated in the model, groundwater discharge to the stream was not controlled by preferential flow in any one layer. Field observations in East Maui, however, show that groundwater discharges in unequal amounts along the reach of a stream with a high proportion of the discharge occurring at springs corresponding to relatively high-permeability layers. Forster & Smith (1988) investigated several factors influencing groundwater flow in mountainous terrain and demonstrated how a single high-permeability layer could be effective in focusing the discharge from a mountainous flow system into a single unit. A more complex numerical model using alternating layers of higher and lower hydraulic conductivity would better simulate patterns of variable discharge along stream reaches but the bulk effective hydraulic conductivity would still be within the range determined from the simple, homogeneous model.

The simple groundwater model incorporates readily available information about recharge and topography and is useful for demonstrating the range of hydraulic conductivity values and anisotropy ratios needed to create a thick groundwater body. A combination of horizontal hydraulic conductivity values determined from the model ranging from 0.08 to 1 m day^{-1} with anisotropy ratios from 1:1 to about 100:1 produce water levels comparable to those observed in East Maui. An estimate of hydraulic conductivity from an aquifer test also falls within this range of hydraulic conductivity values determined from the simulations.

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