A thick lens of fresh groundwater in the southern Lihue Basin, Kauai, Hawaii, USA

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Abstract A thick lens of fresh groundwater exists in a large region of low permeability in the southern Lihue Basin, Kauai, Hawaii, USA. The conventional conceptual model for groundwater occurrence in Hawaii and other shield-volcano islands does not account for such a thick freshwater lens. In the conventional conceptual model, the lava-flow accumulations of which most shield volcanoes are built form large regions of relatively high permeability and thin freshwater lenses. In the southern Lihue Basin, basin-filling lavas and sediments form a large region of low regional hydraulic conductivity, which, in the moist climate of the basin, is saturated nearly to the land surface and water tables are hundreds of meters above sea level within a few kilometers from the coast. Such high water levels in shield-volcano islands were previously thought to exist only under perched or dike-impounded conditions, but in the southern Lihue Basin, high water levels exist in an apparently dike-free, fully saturated aquifer. A new conceptual model of groundwater occurrence in shield-volcano islands is needed to explain conditions in the southern Lihue Basin.

Résumé Dans le sud du bassin de Lihue (Kauai, Hawaii, USA), il existe une épaisse lentille d'eau souterraine douce dans une vaste région à faible perméabilité. Le modèle conceptuel conventionnel pour la présence d'eau souterraine à Hawaii et dans les autres îles de volcans en bouclier ne rend pas compte d'une lentille d'eau douce si épaisse. Dans ce modèle conceptuel, les accumulations de lave dont sont formés la plupart des volcans en bouclier couvrent de vastes régions à relativement forte perméabilité, avec des lentilles d'eau douce peu épaisses. Dans le sud du bassin de Lihue, les laves remplissant le bassin et les sédiments constituent une région étendue à faible conductivité hydraulique régionale, qui, sous le climat humide du bassin, est saturée presque jusqu'à sa surface; les surfaces piézométriques sont plusieurs centaines de mètres au-dessus du niveau de la mer à quelques kilomètres de la côte. On pensait jusqu'à présent que des niveaux piézométriques aussi élevés dans des îles de volcans en bouclier n'existaient que dans le cas de nappes perchées ou de blocage par un dyke, mais dans le sud du bassin de Lihue, des niveaux piézométriques élevés existent dans un aquifère apparemment sans dyke et complètement saturé. Un nouveau modèle conceptuel de présence d'eau souterraine dans les îles de volcans en bouclier est nécessaire pour expliquer les conditions observées dans le sud du bassin de Lihue.

Resumen Se ha determinado la existencia de un espeso lentejón de aguas subterráneas dulces en una extensa región de baja permeabilidad situada al sur de la cuenca de Lihue, en Kauai (Hawaii, Estados Unidos de América). El modelo conceptual convencional de las aguas subterráneas en Hawai y en otros cinturones de islas volcánicas no considera la existencia de lentejones tan gruesos de agua dulce. En dicho modelo, las acumulaciones de flujos de lava que constituyen la mayoría de los cinturones volcánicos se desarrollan en grandes áreas de permeabilidad relativamente baja y con pequeños lentejones de agua dulce. En el sur de la cuenca de Lihue, las lavas de relleno y los sedimentos forman una región extensa de baja conductividad hidráulica regional que, con el clima húmedo de la zona, está saturada hasta prácticamente la superficie del terreno, mientras que el nivel freático se encuentra centenares de metros por encima del nivel del mar a pocos kilómetros de la línea de costa. Se creía hasta ahora que, en los cinturones de islas volcánicas, tales niveles sólo tenían lugar en acuíferos colgados o en condiciones de confinamiento por diques, pero, al sur de la cuenca de Lihue, se dan en acuíferos completamente saturados que no están limitados por diques. Se necesita un nuevo modelo conceptual de las aguas subterráneas en cinturones de islas volcánicas para explicar las condiciones halladas en la cuenca meridional de Lihue.

Keywords Coastal aquifers · Volcanic aquifers · Conceptual models · Island hydrology · Hawaii

Received: 23 October 2001 / Accepted: 14 October 2002
Published online: 27 November 2002

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 DOI 10.1007/s10040-002-0233-5

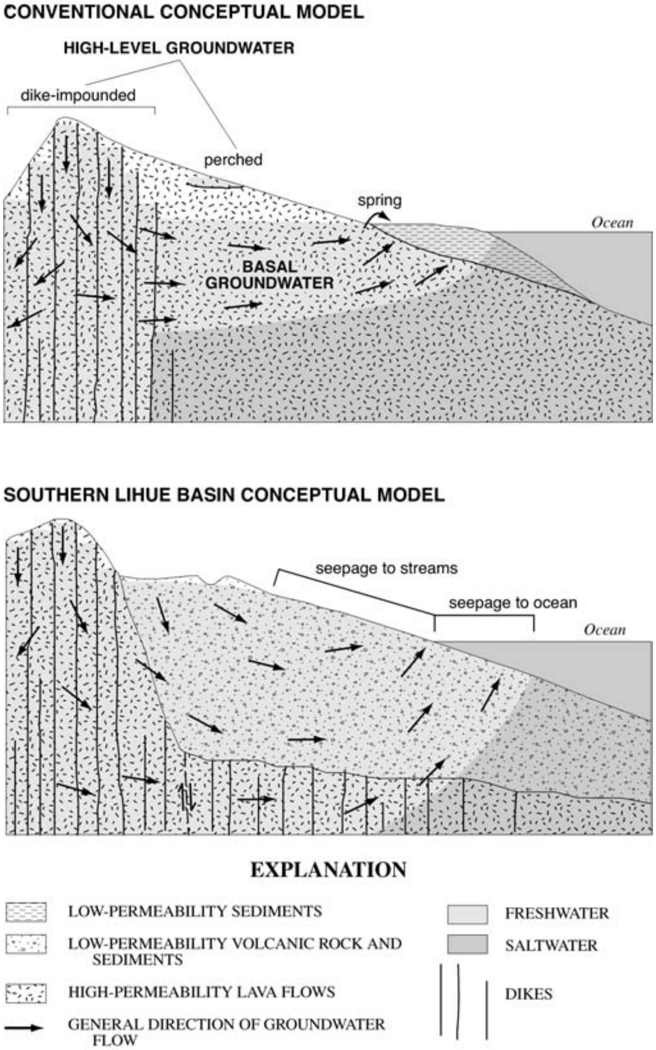


Fig. 1 Diagrammatic cross sections representing conventional conceptual model of groundwater flow in shield-volcano islands, and conceptual model of groundwater flow in the southern Lihue Basin, Kauai, Hawaii

Introduction

Much of the groundwater in an oceanic island forms a lens-shaped body of freshwater overlying saltwater, as shown in Fig. 1. The freshwater lens is buoyed by the density difference between saltwater and freshwater. In the freshwater body, water flows downward in inland parts of the aquifer where recharge is highest, horizontally to the coast, then upward near the coast where groundwater discharges to streams and the ocean. Geologic structure, climate, and size of the island are among a number of factors that impart unique characteristics to each island's groundwater system.

The existence of a freshwater-over-saltwater system was recognized in the shield-volcano islands of Hawaii, USA in the early part of the twentieth century, and by about the middle of the century, the fundamentals of a conceptual model explaining the general modes of occurrence of fresh groundwater had been developed (Lindgren 1903; Meinzer 1930; Stearns and Vaksvik 1935; Stearns 1940; Palmer 1942). This conceptual model, referred to as the "conventional conceptual model", has remained the primary model for groundwater occurrence in Hawaii and has guided groundwater development to the present. However, application of the conventional conceptual model to explore for and manage groundwater in parts of some shield volcanoes, such as the southern Lihue Basin on Kauai, has not been successful because the specific hydrologic characteristics of these areas are not accounted for in the conventional conceptual model.

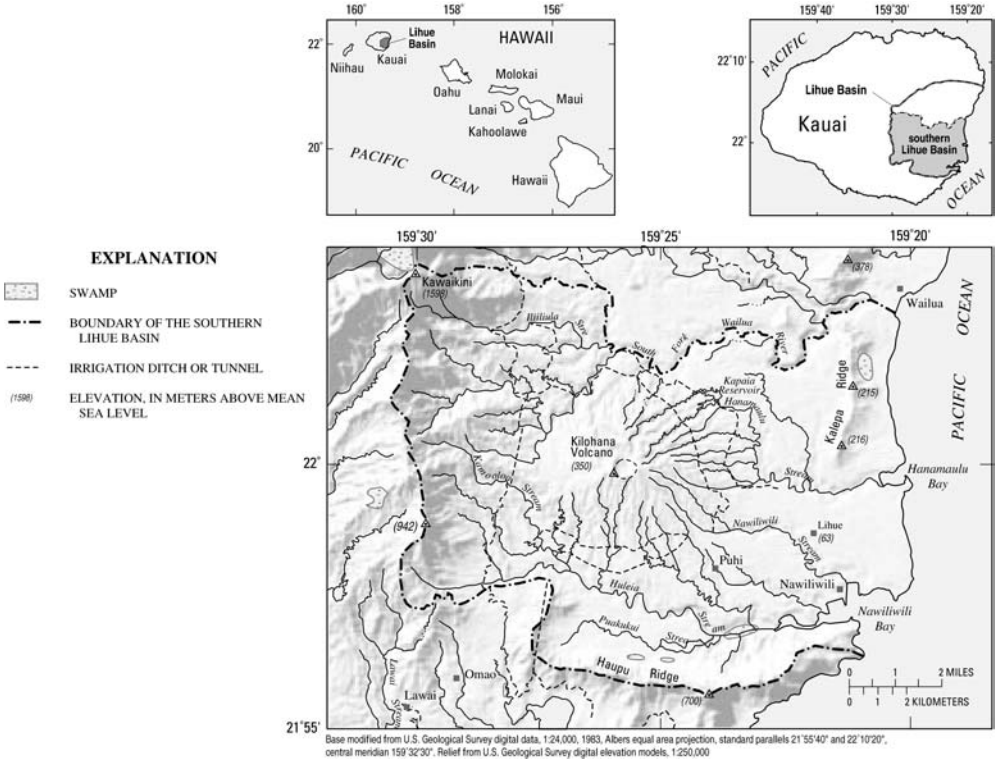
As shown in Fig. 2, the southern Lihue Basin is the southern part of the Lihue Basin, a large semicircular depression in the southeast quadrant of Kauai, the fourth-largest island (1,432 km^2) in the tropical, north-Pacific Hawaiian Archipelago. The southern Lihue Basin comprises the198-km^2 area south of the South Fork Wailua River and north of Haupu Ridge. Geologists have long been aware that the southern Lihue Basin differs geologically from other areas of the Hawaiian islands (Stearns 1946; Macdonald et al. 1960), but the hydrologic implications of the geological differences were not fully recognized in part because Kauai lacked the volume of hydrologic data that was available for more heavily developed islands such as Oahu (on which much of the conventional conceptual model is based). Recent hydrologic studies, including monitor-well drilling and testing, analysis of groundwater discharge to streams, and numerical groundwater modeling (Izuka and Gingerich 1997a, 1997b, 1997c, 1997d, 1998; Gingerich and Izuka 1997a, 1997b; Gingerich 1999), provide compelling evidence that the hydrology of the southern Lihue Basin differs substantially from the conventional conceptual model that has long stood as the paradigm for groundwater occurrence in Hawaii and other shield volcano islands in the Pacific. The purpose of this paper is to present a new conceptual model of groundwater occurrence for the southern Lihue Basin that is consistent with the results of recent studies.

The Conventional Conceptual Model of Groundwater Occurrence in Shield-Volcano Islands

The bulk of a shield volcano is built of many thin basaltic lava flows. Throughout most of this basaltic pile, horizontal hydraulic conductivities (K_h) are hundreds of meters per day, water levels are no more than a few meters above sea level, and the water table slopes gently seaward. In some areas, low-permeability, near-vertical, sheet-like dikes intrude the lava flows and act as hydraulic impediments that impound water within the lava flows and raise water levels to as much as several hundred meters above sea level. Isolated, near-horizontal structures of low vertical permeability, such as ash and soil layers, may create small, perched bodies of water within the otherwise-unsaturated part of basalt lava flows.

 DOI 10.1007/s10040-002-0233-5

Fig. 2 Location of the southern Lihue Basin, Kauai, Hawaii



In the conventional conceptual model, groundwater in shield-volcano islands is classified as either basal or high-level groundwater (Fig. 1). The term “basal water,” as first used by Meinzer (1930), refers to the groundwater that is below the lowest or “main” water table. Meinzer’s definition further requires that the basal water beneath the main water table completely saturates the aquifer, and thereby distinguishes basal groundwater from perched groundwater, which by definition must be underlain by an unsaturated aquifer. In shield volcano islands, the largest basal groundwater bodies exist in high-permeability, dike-free, lava-flow aquifers. On the Hawaiian island of Oahu, a wedge of low-permeability coastal sediments creates a semiconfining unit known locally as caprock, which impedes coastal discharge and causes heads in the basal water to rise. Even so, basal water levels on Oahu are less than 15 m above sea level (Hunt 1996). Basal water bodies in islands with no caprock or thinner caprock than Oahu have lower water tables (Meinzer 1930).

High-level groundwater includes perched groundwater as well as groundwater impounded by dikes. Whereas perched groundwater is underlain by unsaturated rock, dike-impounded groundwater bodies may be fully saturated from the water table to sea level. No particular water level distinguishes high-level groundwater from basal groundwater; the distinction is made primarily on the basis of associated geologic structures. Even without definitive evidence of associated geologic structures, however, some groundwater bodies have been assumed to be high level because their water levels were higher than previously identified basal groundwater systems. Most of these enigmatic high-level groundwater bodies were presumed to be impounded by unseen low-permeability, vertically oriented, structures such as dikes or buried ridges (Stearns 1940; Oki 1998, 1999).

If the high water levels were not in an area presumed to have dikes, it was often presumed to be perched. Macdonald et al. (1960) presumed that high-elevation springs, gaining streams, and water-development tunnels in the Lihue Basin were fed by perched groundwater bodies. This presumption, however, was made at a time when few vertical wells existed in the southern Lihue Basin (except in the surrounding ridges), and with few indications of regional aquifer permeability. Since then, numerous wells having low specific capacity were drilled, which indicated that the aquifer beneath much of the southern Lihue Basin has much lower permeability than other shield volcanoes.

Hydrogeology of the Southern Lihue Basin

Precipitation in the southern Lihue Basin is heaviest where the prevailing northeasterly trade winds encounter the windward flanks of Kauai’s central mountains, forcing warm, moist air into the cool, higher elevations, as shown in Fig. 3. Average annual rainfall ranges from about 1,270 mm/year in low-lying coastal areas to more than 11,000 mm/year near the crest of Kauai’s central mountains (Giambelluca et al. 1986).

A prominent feature in the southern Lihue Basin is the broad dome of Kilohana Volcano. The crater at the summit of Kilohana Volcano has a marsh, and numerous

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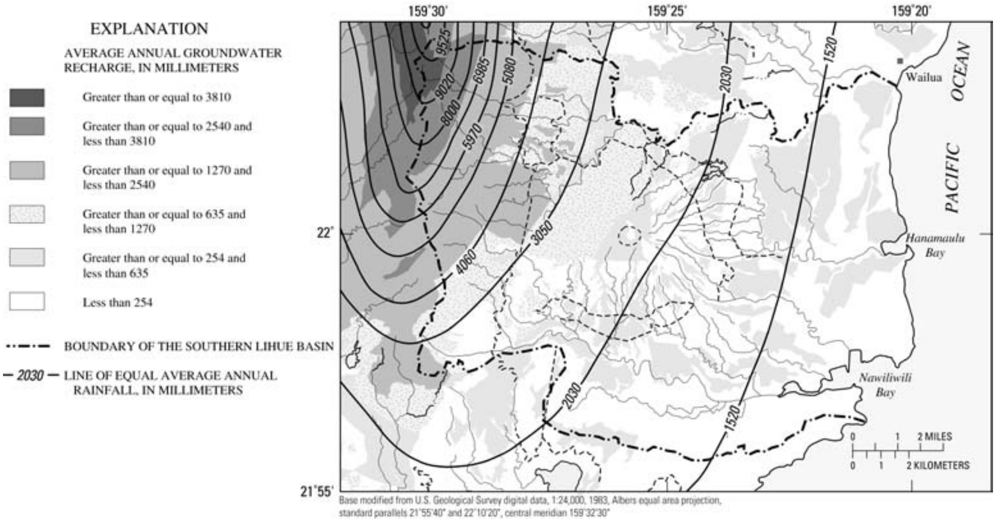

Fig. 3 Rainfall and recharge in the southern Lihue Basin, Kauai, Hawaii (from Giambelluca et al. 1986; Shade 1995)

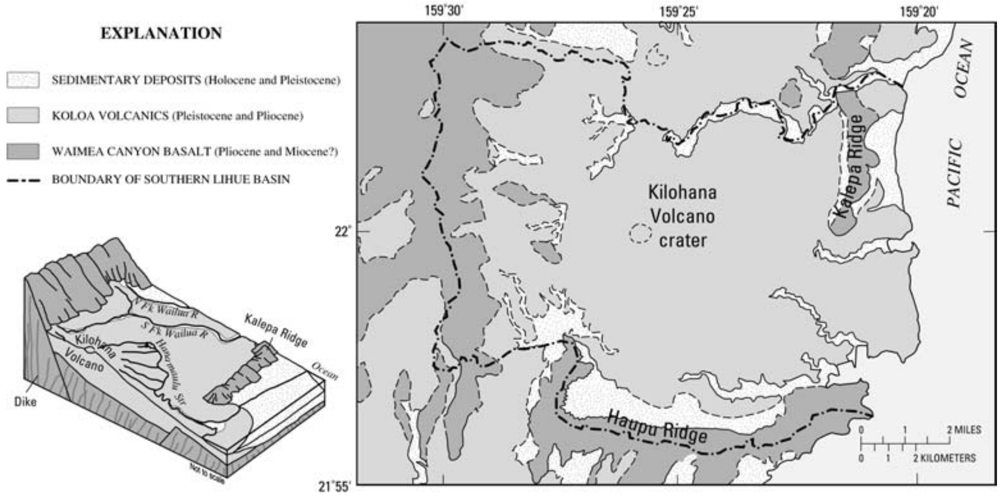

Fig. 4 Geology of the southern Lihue Basin, Kauai, Hawaii (modified from Macdonald et al. 1960)

perennial streams drain from the flank of the volcano. The marsh and perennial streams indicate that the groundwater table is at or near the surface for most of the area of the volcano. During most of the twentieth century, including the period during which the data for this study were gathered, much of the gently sloping land in the southern Lihue Basin was used for sugarcane cultivation. The sugar industry built and maintained ditches and reservoirs that not only diverted and stored stream flow within the basin for irrigation, but also brought water in from and took water out to adjacent basins. The natural drainage pattern of the southern Lihue Basin had thus been modified into a network of natural stream channels crossed by agricultural ditches.

Geologic Structure and Hydraulic Properties of the Rocks

According to previous geologic investigations (Stearns 1946; Macdonald et al. 1960; Krivoy et al. 1965; Clague and Dalrymple 1988; Langenheim and Clague 1987; Moore et al. 1989; Holcomb et al. 1997; Reiners et al. 1999), Kauai was built during the Pliocene by mid-plate, hot-spot volcanism which created one or more large shield volcanoes. Subsequent erosion and faulting created large valleys, canyons, and other depressions, including the Lihue Basin. These depressions were later partially filled with hundreds of meters of sediments as well as lava flows from rejuvenated volcanism during the Pliocene and Pleistocene.

The consolidated rocks of the southern Lihue Basin are divided into two geologic formations separated by an erosional unconformity. As shown in Fig. 4, the older and more voluminous Waimea Canyon Basalt forms the basement as well as the ridges and mountains surrounding the basin. Resting unconformably on the Waimea Canyon Basalt is the formation known as the Koloa Volcanics, a heterogeneous unit of variably weathered, thick, massive lava flows, pyroclastic deposits, and intercalated sediments that fill depressions in the Waimea Canyon Basalt (Macdonald et al. 1960; Langenheim and Clague 1987). The thickness of the Koloa Volcanics ranges from zero to more than 150 m (Macdonald et al. 1960; Reiners et al. 1999). Small volumes of sediments

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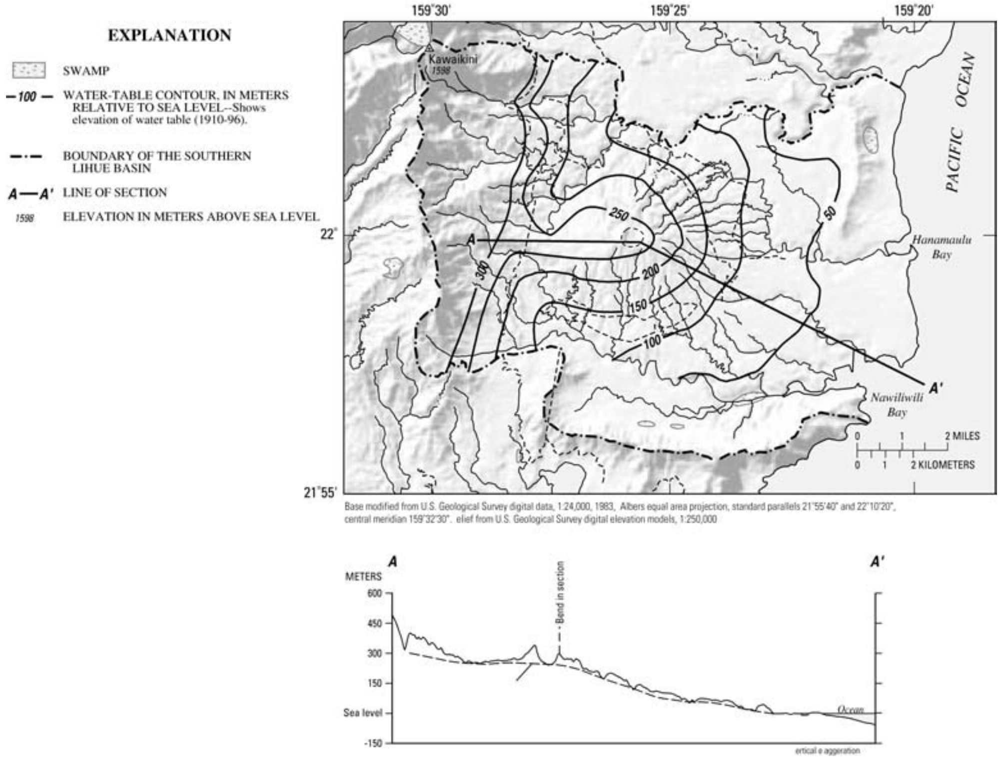

Fig. 5 Water-table map and profile generalized from data from 1910 through 1996 for the southern Lihue Basin, Kauai, Hawaii (modified from Izuka and Gingerich 1998)

of Pleistocene and Holocene age lie at the surface, but have relatively minor hydrologic significance.

Throughout most of Kauai, the Waimea Canyon Basalt consists mainly of thin lava flows, but in the southern Lihue basin, the lava flows are intruded by near-vertical, sheet-like volcanic dikes (Macdonald et al. 1960). Dikes reduce the K_h of the intruded lava flows. An aquifer test of the dike-intruded Waimea Canyon Basalt on the southern edge of the southern Lihue Basin on Haupu Ridge indicates a K_h of 5.2 m/day (Gingerich 1999), but this estimate is for rocks only in the immediate vicinity of the well. The regional bulk K_h of the dike-intruded Waimea Canyon Basalt is probably lower because of dikes that lie beyond the reach of the aquifer test (Izuka and Gingerich 1998). The K_h of the thick, dense, lava flows and intercalated sediments of the Koloa Volcanics varies widely in the southern Lihue Basin, but areas of high K_h are rare and of limited extent. Aquifer tests indicate that K_h ranges from about 0.02 m/day to about 40 m/day (Gingerich 1999), but the regional K_h is less than 0.3 m/day (Izuka and Gingerich 1998).

Groundwater Levels

Water-level elevations in wells are near sea level at the coast but increase steeply with distance inland. Many wells in the southern Lihue Basin have water levels more than 100 m above sea level, even when the wells penetrate more than a 100 m below sea level, which indicates that the high water levels are part of a groundwater system that is not perched, as previously thought. Figure 5 shows a water-table map compiled by Izuka and Gingerich (1998) using water-level data from wells, springs, seeps, and marshes. Because the map was compiled from water-level data collected over several decades, it does not represent any instant in time, and short-term temporal variations in the water table may not be accurately depicted. However, the map gives a view of the regional water table generalized over time, and shows that steep horizontal head gradients are characteristic throughout much of the southern Lihue Basin. The steep gradients are consistent with the low K_h characteristic of the Koloa Volcanics. Gradients are steepest where streams incise the aquifer and flatter where few streams drain the groundwater. In a sense, streams that incise the upper aquifer act as drains that shape the water table and are probably the principal reason that water levels in the rest of the basin remain below the ground surface.

Groundwater Recharge

Shade (1995) used a water-budget model to compute recharge on Kauai based on conditions that existed in 1990, and estimated that the southern Lihue Basin receives about 4.76 m^3/s of groundwater recharge, as shown in Table 1. Near the northwest corner of the southern Lihue Basin (Fig. 2), recharge exceeds 3,810 mm/year, whereas in the coastal areas, recharge is less than 254 mm/year (Fig. 3). In drier areas, the recharge distribution departs from the rainfall distribution because of infiltration of excess irrigation water and variations in soil-moisture storage capacity.

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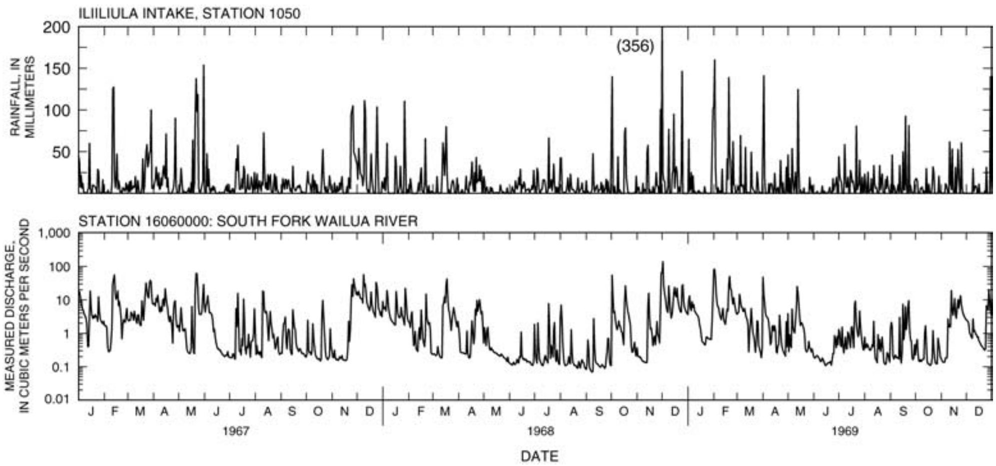

Fig. 6 Rainfall and hydrograph from typical stream in the southern Lihue Basin Kauai, Hawaii

Table 1 Summary of groundwater flows (mass balance) in the southern Lihue Basin, Kauai, Hawaii

	Estimate		Model-simulated flow[a] (m^3/s)
	Period to which estimate applies	Flow (m^3/s)	
Recharge	1990	4.76[b]	4.76
Groundwater withdrawal	1993	0.17	0.17
Discharge to streams and rivers	1913–1970	3.58 to 4.40[a]	3.19
Subsurface flow out of basin (includes flow to adjacent groundwaterareas and discharge to ocean)	Not applicable	0.19 to 1.01	0.68

[a] From Izuka and Gingerich (1998); [b] From Shade (1995)

To estimate recharge in the southern Lihue Basin, Shade (1995) used a monthly water budget, which can substantially over or underestimate recharge, and did not include contribution from fog condensation. Izuka and Oki (2002) evaluated the uncertainty resulting from Shade's methods and determined that the recharge estimates have an uncertainty ranging from at least –13 to +1.6%. Although uncertainty exists, Shade's recharge estimates indicate that groundwater recharge in the southern Lihue Basin is substantial.

Groundwater Withdrawal

Groundwater in the southern Lihue Basin is withdrawn by conventional vertical wells as well as water-development tunnels that were bored horizontally into stream banks to intercept some of the natural groundwater discharge to the streams. Izuka and Gingerich (1998) estimated groundwater withdrawal from wells and tunnels in the southern Lihue Basin to be about 0.17 m^3/s (Table 1) based on data obtained from the Hawaii State Commission on Water Resource Management in 1993, but acknowledged that this number may represent only about 70% of the actual withdrawal because not all wells had meters.

Because the southern Lihue Basin is defined on the basis of topographic features, not groundwater barriers or divides, effects from withdrawals theoretically have the potential to cross basin boundaries. However, groundwater withdrawal from the area to the north is relatively small and unlikely to cause effects that can cross the groundwater barrier presented by the South Fork Wailua River. No such barrier exists to the south and east of the southern Lihue Basin, therefore it is possible that some of the 0.58 m^3/day that was being withdrawn from wells immediately to the southwest of the southern Lihue Basin originates from recharge within the basin.

Groundwater Discharge to Streams and the Ocean

Groundwater flowing through the southern Lihue Basin discharges subaerially at springs and along streams and rivers, as well as directly to the ocean via coastal and submarine seepage. As shown in Fig. 6, hydrographs from stream gages in the Lihue Basin show flashy discharge peaks coincident with rainfall, but between the peaks, substantial base flow (i.e., groundwater discharge) persists in the streams.

Hydrograph-separation analyses used to estimate base flow from stream-gage data indicate that the total base flow for the gaged reaches of major streams (South Fork Wailua River, Hanamaulu Stream, and Huleia Stream), averages 3.58 to 4.40 m^3/s, as shown in Tables 1 and 2; the total base flow from all streams in the basin is probably higher because base flow in ungauged reaches were not included in this total. Because of the limits imposed

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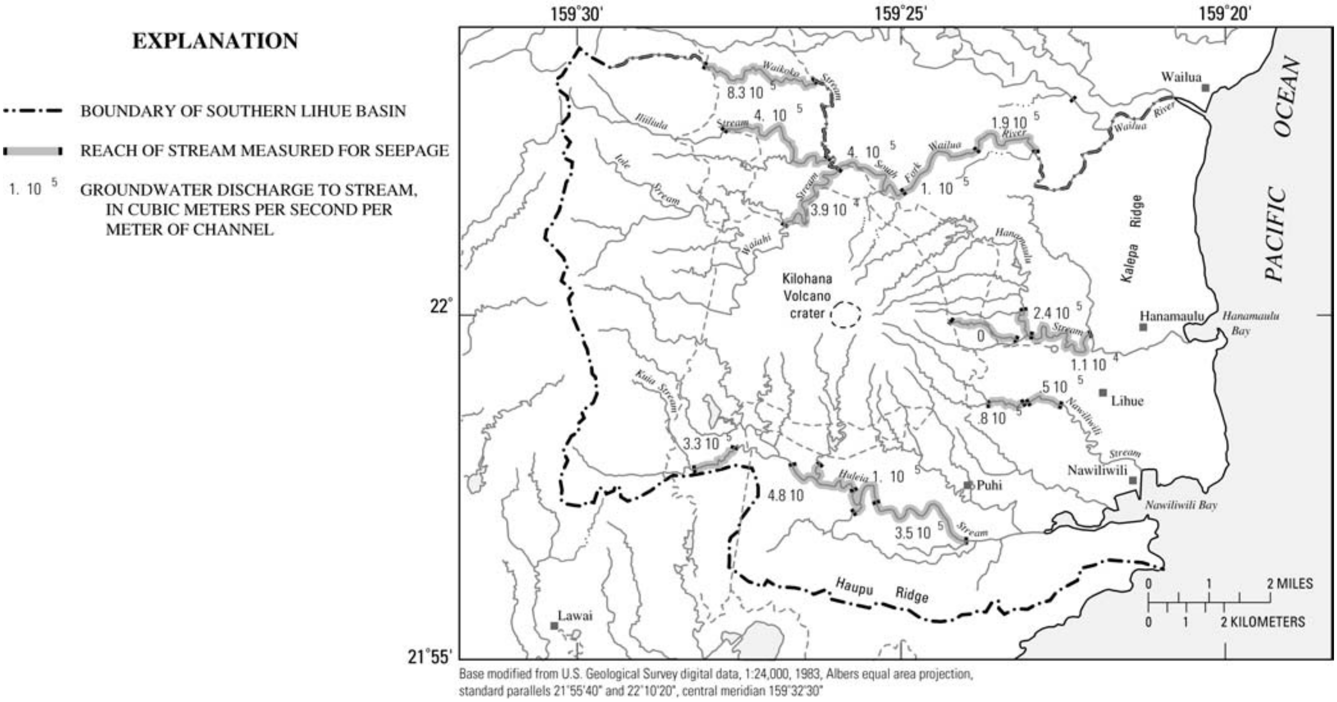

Fig. 7 Groundwater discharge (in $m^3\ s^{-1}\ m^{-1}$ of channel), from instantaneous discharge measurements, to selected streams in the southern Lihue Basin, Kauai, Hawaii

Table 2 Groundwater discharge to selected streams and rivers in the southern Lihue Basin, Kauai, Hawaii (from Izuka and Gingerich 1998)

Stream/river	Estimated groundwater discharge from analysis of stream-gauge data		Model-simulated groundwater discharge (m^3/s)
	Period used in analysis	Groundwater discharge (m^3/s)	
South Fork Wailua River	1913, 1918	2.49 to 3.26	2.44
Hanamaulu Stream	1911–1913	0.14 to 0.20	0.17
Huleia Stream	1968–1970	0.95	0.53
Nawiliwili Stream		No data	0.05

by the availability of stream-gauge data, these base-flow estimates do not represent a concurrent period of time, but temporal variations in base flow are likely to be small relative to the large persistent base flows characteristic of the streams in the southern Lihue Basin. The persistence of base flows is evident in recent direct, instantaneous (i.e., not estimated from gauge data) base-flow measurements, as shown in Fig. 7. The measurements indicate that most reaches of rivers and streams, even those without gauges or those having small drainage areas, continue to receive substantial groundwater discharge consistent with the base flows estimated from stream gauge data.

Comparison of the base-flow and recharge estimates for the southern Lihue Basin indicate that groundwater discharge to streams constitutes at least 75% of the estimated 4.76 m^3/s of recharge the southern Lihue Basin receives. Although small amounts of groundwater may cross basin boundaries, and uncertainties in the recharge and base-flow estimates impart some imprecision in the mass-balance computations, the data indicate that most of the water recharging the southern Lihue Basin aquifer is eventually discharged subaerially to streams rather than directly to the ocean (Table 1).

A Conceptual Groundwater Model for the Southern Lihue Basin

Many of the observed hydrogeologic characteristics of the southern Lihue Basin are not consistent with the conventional conceptual model of groundwater occurrence in shield-volcano islands. The groundwater system in the southern Lihue Basin is characterized by flow through low-permeability rocks, which produces a thick freshwater lens and steep head gradients, and causes the water table to rise from near sea level at the coast to hundreds of meters above sea level a few kilometers inland (Figs. 1 and 5). In most places, the water table lies only a few meters below the ground surface. The draining of the aquifer by streams shapes the water table, and groundwater discharge through streams and springs con-

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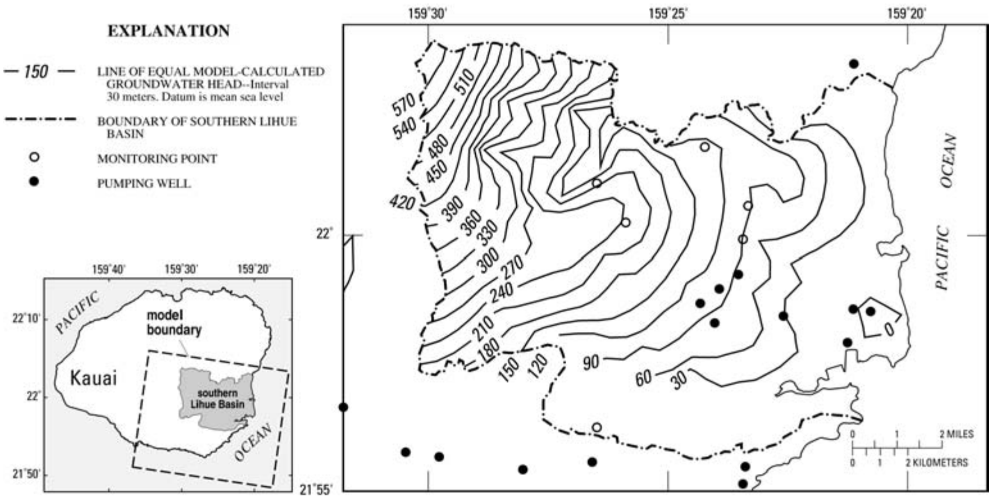

Fig. 8 Distribution of simulated head in the steady-state numerical groundwater model of the southern Lihue Basin, Kauai, Hawaii (modified from Izuka and Gingerich 1998)

stitutes the main path for natural outflow from the aquifer; a lesser amount discharges at or beyond the coast.

In contrast, aquifers containing basal groundwater on Oahu have hydraulic conductivities one to several orders of magnitude higher than those in the southern Lihue Basin (Soroos 1973). The "basal" and "high-level" classifications of the conventional conceptual model do not account for the mode of occurrence of groundwater in the southern Lihue basin, where water levels may be hundreds of meters above sea level, not because of perching or dike impoundment, but because of low regional permeabilities in an aquifer in a moist climate. The conventional conceptual model for groundwater occurrence in shield-volcano islands does not account for an extensive region of low-permeability such as that formed by the Koloa Volcanics in the southern Lihue Basin.

Quantitative Consistency of the Southern Lihue Basin Conceptual Model

The conceptual model of groundwater occurrence in the southern Lihue Basin described here differs substantially from the conventional conceptual model, but the southern Lihue Basin conceptual model is consistent with the stream-flow, aquifer hydraulics, and water-level data. Izuka and Gingerich (1998) developed a numerical model of the southern Lihue Basin that shows that the conceptual model is also quantitatively consistent with the observed data. The reader is referred to Izuka and Gingerich (1998) for details of the model construction; a synopsis of the model description is given here.

Izuka and Gingerich (1998) developed a steady-state model using the finite-difference modeling program SHARP (Essaid 1990), which allows simulation of coupled freshwater and saltwater flow. The model encompassed not only the Lihue basin, but also adjacent parts of Kauai and offshore areas, as shown in Fig. 8, so that the no-flow boundaries required at the periphery of the model would coincide with natural no-flow boundaries or groundwater divides. The model had two layers and nearly 5,000 elements, each representing an area of 0.37 km^2. Each element was assigned hydraulic properties consistent with available data on geologic structure and results from aquifer tests in the southern Lihue Basin, or estimates of hydraulic properties from similar aquifers in Hawaii (Soroos 1973; Souza and Voss 1987; Hunt 1996; Gingerich 1999).

The resulting model-simulated water levels are generally consistent with observed groundwater levels in the southern Lihue Basin. Comparison of Figs. 5 and 8 shows that despite minor differences that can be attributed to the limits imposed by model discretization, the model reproduces major characteristics of the water-table map such as the high groundwater levels and the depression of the water table where streams incise the aquifer. The numerical groundwater model shows that low hydraulic conductivities consistent with field-test data in the southern Lihue Basin will result in steep horizontal groundwater gradients and water levels that are hundreds of meters above sea level in a fully saturated (not perched) system. The model-simulated base flows are also consistent with observed base flow estimates from analysis of stream-gage data from the southern Lihue Basin (Tables 1 and 2). The model and stream-gauge data analysis both show that most of the groundwater flowing through the southern Lihue Basin discharges to streams rather to the ocean.

Conclusions

The groundwater system in the southern Lihue Basin is characterized by flow through low-permeability rocks, which produces a thick freshwater lens, steep head gradients, and a water table that rises from near sea level at the coast to hundreds of meters above sea level a few kilometers inland. In most places, water saturates the ground nearly to the surface. Subaerial groundwater discharge through streams shapes the water table and constitutes the main path for natural outflow from the aquifer; a lesser amount discharges at or beyond the coast.

 DOI 10.1007/s10040-002-0233-5

These characteristics of the groundwater system in the southern Lihue Basin differ from the conventional conceptual model for groundwater occurrence on shield-volcano islands. Neither the conventional basal-groundwater conceptualization, in which water tables are everywhere less than 15 m, nor the conventional high-level-groundwater conceptualization, in which water is either impounded by dikes or perched, adequately explains groundwater occurrence in the southern Lihue Basin, where water levels may be hundreds of meters above sea level without being perched or impounded by dikes. The conventional conceptual model does not account for the large region of low-permeability rock formed by the accumulation of thick, dense, lava flows and intercalated sediments in the southern Lihue Basin.

Acknowledgements This study was funded through a cooperative agreement between the County of Kauai Department of Water and the US Geological Survey.

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DOI 10.1007/s10040-002-0233-5