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The influence of microclimates and fog on stable isotope signatures used in interpretation of regional hydrology: East Maui, Hawaii

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ABSTRACT

Stable isotopes of precipitation, ground water and surface water measured on the windward side of East Maui from 0 to 3055 m altitude were used to determine recharge sources for stream flow and ground water. Correct interpretation of the hydrology using rainfall $\delta^{18}O$ gradients with altitude required consideration of the influence of fog, as fog samples had isotopic signatures enriched by as much as 3‰ in $\delta^{18}O$ and 21‰ in δD compared to volume-weighted average precipitation at the same altitude. The isotopic analyses suggested that fog drip was a major component of stream flow and shallow ground water at higher altitudes in the watershed. Oxygen-18/altitude gradients in rainfall were comparable for similar microclimates on Maui (this study) and Hawaii Island (1990-95 study), however, East Maui $\delta^{18}O$ values for rain in trade-wind and high-altitude microclimates were enriched compared to those from Hawaii Island. Isotopes were used to interpret regional hydrology in this volcanic island aquifer system. In part of the study area, stable isotopes indicate discharge of ground water recharged at least 1000 m above the sample site. This deep-flowpath ground water was found in springs from sea level up to 240 m altitude, indicating saturation to altitudes much higher than a typical freshwater lens. These findings help in predicting the effects of ground water development on stream flow in the area.

INTRODUCTION

In a previous study on Hawaii Island, *Scholl et al.* (1996) found that isotope/altitude gradients were distinctly different according to the microclimates in the study area, and correct interpretation of regional hydrology using $\delta^{18}O$ and δD required understanding the microclimate of the recharge area. For the study discussed herein, we tested the hypothesis that isotope /altitude gradients on another island were predict-able based on knowledge of micro-climates. In addition, the regional hydrology was investigated using stable isotopes, as increasing growth and development on the Hawaiian island of Maui has generated interest in the ground water resources of the windward area of East Maui. An understanding of ground water-surface water interactions in the area is necessary to determine the possible effects of ground water withdrawal on nearby streams.

East Maui Volcano (Haleakala) is the entire eastern part of the Island of Maui (Figure 1). It is a basaltic shield volcano like those forming the other Hawaiian Islands. The study area encompasses three microclimates: rain-shadow, windward slope (trade-wind), and high-altitude (Figure 2). The interpretation of regional hydrology focused on the northeast-facing slope of the volcano, in the area from Maliko Gulch in the west to Waianapanapa on the east (Figure 1). The western part of the study area is accessible by road up to Haleakala summit

(3055 m), but altitudes higher than about 460 m are not readily accessible in the eastern part.

Water-bearing units of the region consist of layered basalts from several different eruptive episodes in the volcano's history, and minor sedimentary alluvial deposits in valleys that were submerged during the last high stand of sea level. In general, permeability of the basalt units varies according to the thickness of individual lava flows in an eruptive episode. Permeability is usually associated with lava flow tops, so a unit with many thin layers will have higher permeability than a unit with a few thick, dense flows.

Mean annual temperatures in the study area range from 24˚C near sea level (14 m) to about 10˚C at Haleakala summit (3055 m), and the summer-to-winter temperature variation is only about 4.5˚C *(Nullet and Sanderson, 1993)*. The climate is dominated by trade winds from the east-northeast, which are present more than 90% of the time during summer months, and somewhat less frequently in winter. The ground water study area is in the trade-wind microclimate, which receives near-daily orographic rainfall ranging from 1500 to >7000 mm per year (Figure 2; *Giambelluca et al., 1986)*. Potential evapotranspiration and evaporation are lowest between about 900 and 2400 m on the mountain slope, due to the pervasive cloud cover *(Kitayama and Mueller-Dombois, 1994)*. The rain-shadow microclimate on the western slope of Haleakala is caused by the trade winds flowing downslope; rainfall in this area is usually from frontal systems or storms, and is 750 mm/year or less. The high-altitude microclimate is above a temperature inversion that occurs in the atmosphere under trade-wind conditions; the altitude of the inversion varies, averaging 2000 m above sea level. Because trade-wind clouds evaporate in the dry air above the inversion, it acts as a climatological boundary in the Hawaiian

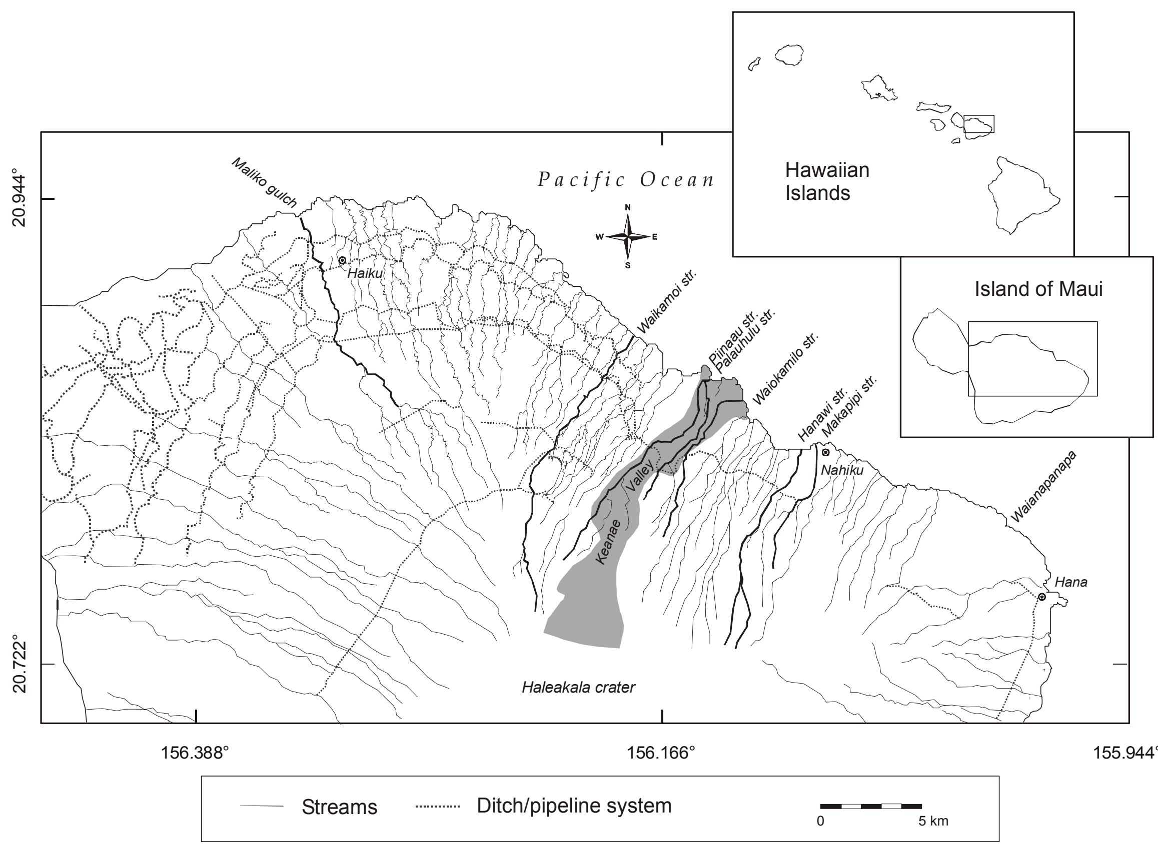

Figure 1. Location map showing the study area in East Maui, Hawaii. The ground water system discussed in this paper extends from Maliko Gulch on the west to Waianapanapa on the east. Streams to the southwest of Maliko Gulch are ephemeral.

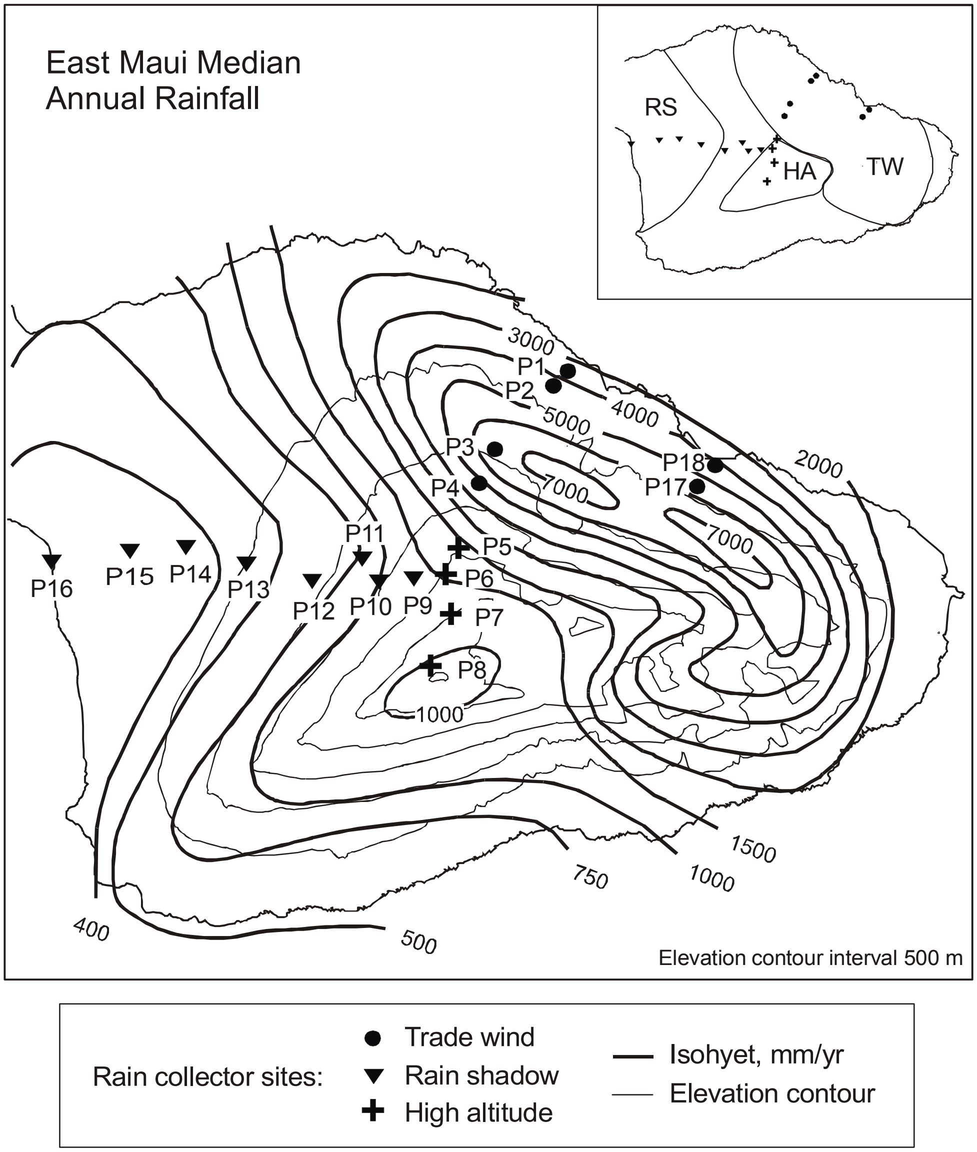

Figure 2. Location of isotope rain collector sites and contours of median annual rainfall on East Maui, in millimeters per year, adapted from *Giambelluca et al., 1986*. Small map shows the trade-wind (TW), rain-shadow (RS) and high-altitude (HA) microclimates, as defined for this study.

islands; rainfall above the inversion is predominantly from storms or frontal systems *(Schroeder, 1993)*.

A network of closely-spaced streams drains the windward slope of the volcano. Historically, much of this stream flow has been collected in a system of ditches and tunnels (Figure 1) and transported to the dry, west-facing slope of East Maui Volcano to be used for agriculture and drinking water. Recharge in the study area is from rainfall and fog drip, a result of cloud droplets impacting the vegetation. Fog drip has not been quantified in this area, and rainfall is measured daily or monthly at stations in areas with road access, generally at the lower altitudes. In the study area, recharge amount is assumed to correlate with rainfall, and is estimated to be 41% of annual rainfall plus estimated fog drip *(Shade, 1999)*.

The traditional conceptual model for ground water occurrence in the Hawaiian Islands divided ground water into three types: basal fresh water lens, perched water, and dike-impounded water *(Stearns and Macdonald, 1942)*. It was assumed that the high permeability of the basalt flows precluded the development of freshwater lenses with heads greater than a few meters above sea level. Evidence from more recent studies in the Hawaiian Islands *(Gingerich, 1999a; Izuka and Gingerich, 1998; Kauahikaua et al., 1998; Meyer, 2000)* suggests that in some areas, the basalt flows are fully saturated to altitudes high above sea level, with the water table much closer to land surface than previously reported.

The sparse and uneven distribution of wells on East Maui makes it difficult to obtain information on subsurface aquifer configurations. If altitude variation is large enough, stable isotopes work well as regional hydrologic tracers in areas with few wells, because the stable isotopes of water in precipitation, ^{2}H and ^{18}O, vary with altitude under conditions of progressive condensation from a vapor mass, as occurs with orographic rainfall *(Dansgaard, 1964)*. *Siegenthaler and Oeschger (1980)* noted that other factors, such as isotopic enrichment of falling raindrops due to equilibration with ambient vapor, affect the isotopic signature of precipitation, and the local $\delta^{18}O$/ altitude relation must be determined for hydrological applications. Previous studies on Hawaii Island (*McMurtry et al., 1977, Scholl et al., 1996)*, Cheju Island, Korea *(Davis et al., 1970, Lee et al., 1999)*, in Oregon *(Ingebritsen et al., 1989, James et al., 2000)* and Japan *(Yasuhara et al., 1997)* have all successfully used stable isotopes to interpret regional hydrology in volcanic terrain.

The purpose of this study was twofold: 1) to test whether isotope/altitude gradients in rainfall on Maui were similar to those found for comparable microclimates on Hawaii Island *(Scholl et al., 1996)*; and 2) to use stable isotopes as tracers to determine the source of water in streams, springs and wells. Transects of precipitation isotope collectors were sampled semi-annually for two years, and the results showed that isotope/altitude gradients were similar to those on Hawaii Island, but slightly offset, with the Maui samples isotopically enriched (Figure 3A). Stable isotope signatures were used to classify ground water and stream baseflow as shallow (locally recharged) or deep (recharged at high altitude), allowing insight into the structure of the regional aquifer system. The results suggest a vertically extensive body of ground water in the Keanae valley up to about 300 m altitude. The isotopes provide evidence that this ground water body exists in the area east of Keanae valley, but cannot define its extent. Isotopic evidence also indicates that fog drip appears to be a major component of stream flow and high-altitude springs, highlighting the role of fog as an important, and possibly underestimated, water source on East Maui.

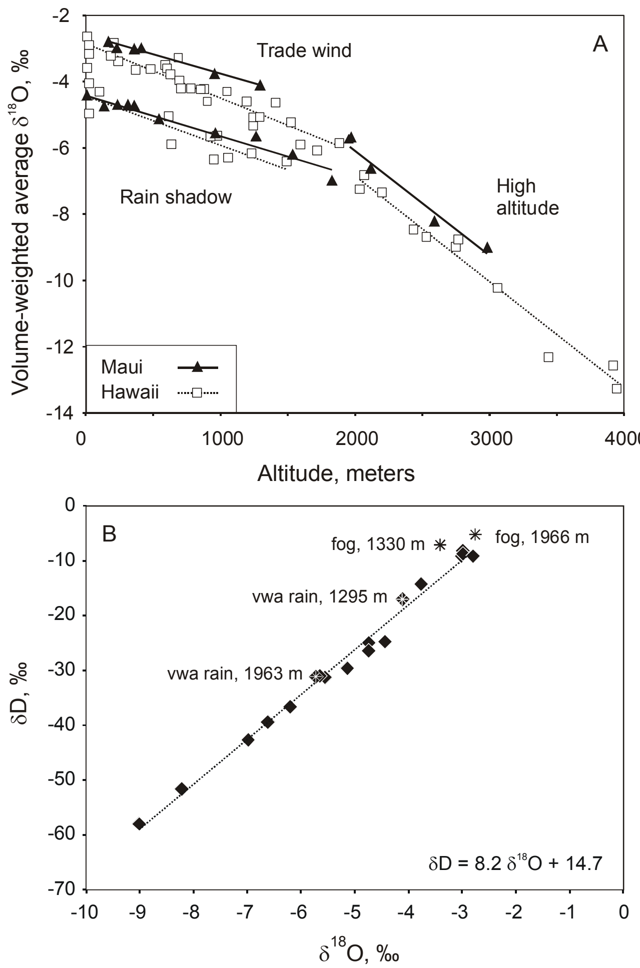

Figure 3.
A. Comparison of $\delta^{18}O$ / altitude gradients on East Maui (data in Table 2) and Hawaii Island (data in Scholl et al., 1995), (m is altitude, in meters).
Maui trade wind: $\delta^{18}O = -0.00116(m) - 2.62$
Hawaii trade wind: $\delta^{18}O = -0.00164(m) - 2.85$
Maui high altitude: $\delta^{18}O = -0.0032(m) + 0.258$
Hawaii high altitude: $\delta^{18}O = -0.0032(m) - 0.454$
Maui rain shadow: $\delta^{18}O = -0.00123(m) - 4.42$
Hawaii rain shadow: $\delta^{18}O = -0.00148(m) - 4.44$
B. Local meteoric water line for East Maui, using volume-weighted average (vwa) precipitation samples, with fog samples shown for comparison.

METHODS

Sample Collection

Precipitation

Precipitation collectors were placed at six sites in the trade-wind rainfall area, at eight sites in the rain shadow area, and at four sites in the high-altitude rainfall zone (Figure 2). All the data except those from the rain-shadow area were used for the ground water analysis, these included two collectors along Hanawi Stream in the middle of the trade-wind rainfall area, and five collectors in a transect extending from 229 to 1963 m altitude along Waikamoi Stream on the western side of the high-rainfall area, continuing with three collectors placed from 2118 to 2984 m at Haleakala summit.

Collectors were 3.5- or 5-gallon HDPE buckets with funnels set in the lid (funnels had variable diameters calibrated for expected rainfall volume), and containing a 1-cm layer of mineral oil to prevent evaporation, as described in *Scholl et al. (1996)*. The collectors were left in place for six months to obtain a cumulative precipitation sample. At the end of each collection period, the sample volume was measured and subsamples were taken for stable isotope analysis. Precipitation samples were collected from September 1995 through September 1997, including two fall/winter periods and two spring /summer periods. Rainfall during September-December 1995 and throughout 1996 was generally below normal, and in 1997 was slightly above normal *(National Climatic Data Center, 1995-97)*. A volume-weighted average isotopic composition was calculated for each sample site, these average compositions were plotted by altitude, and linear regressions were fitted to obtain the gradients of precipitation $\delta^{18}O$ composition with altitude in trade-wind, rain-shadow, and high elevation areas (Figure 3A). There is a gap between the 'trade-wind' and 'high-altitude' gradients for Maui as there was no precipitation collector placed between 1295 and 1963 m altitude. Gradients for Hawaii Island *(Scholl et al., 1996)* are shown for comparison.

The orographic rainfall process that accounts for the near-daily precipitation in the trade-wind area involves clouds that form when the airflow over the Pacific Ocean reaches Maui. Moist air is lifted along the slopes of Haleakala, cooling until the dew point is reached and vapor condensation occurs. Upward progress of the air mass is limited by the inversion layer, so that the clouds do not always extend to the highest altitudes on the mountain. The amount of rain in any location along the slope is determined by the cloud dynamics and height – the inversion layer altitude is generally below 3000 m, and the cloud base is around 600 m *(Giambelluca and Nullet, 1991; Takahashi, 1981)*. Precipitation in the study area above the cloud base consists of horizontally wind-blown cloud water: fog, drizzle and rain. Proportions of fog and rain may change with altitude on the mountain slope, depending on how far the cloud top is above the slope. It is probable that our horizontally-oriented funnels placed near the ground collected mostly larger rain drops, and did not collect fog and drizzle in the proportions present in the total precipitation.

Fog has been found to have an isotopic signature that is more enriched (heavier) than rainfall for the same altitude *(Ingraham and Matthews, 1990, 1995; Aravena et al., 1989)*. Fog-drip collectors were deployed for two one-week periods, after the stream isotope data for this study suggested that fog was an important component of stream flow at higher altitudes. The fog collector was adapted from the design of *Schemenauer and Cereceda (1994)*, and had shade cloth screening stretched on a frame on which wind-blown fog collected then dripped into a collection trough, then into a bottle containing mineral oil to prevent evaporation. The collector was placed at 1330 m altitude for one week, in April 2000, and at 1966 m for one week in May 2001. A funnel-and-bottle rain isotope collector was also placed at each site to correct for any rainfall that the fog collector may have intercepted. The small amount of sample found in the rain collectors at each site had nearly the same isotopic composition as the fog sample (Table 1), suggesting that drizzle and fog collected on the funnel surface. It probably did not rain heavily at either site during the week of collection. Data from the two nearest daily-record stations show normal conditions during

Table 1. Isotopic composition and volume for two one-week fog (screen collector) and rain (funnel collector) samples collected near site P4 at 1330 m in April 2000, and at site P5 at 1966 m in May, 2001. *Enrichment refers to the comparison of fog with volume-weighted average rainfall from the site.

Altitude, m	Fog $\delta^{18}O$, δD (‰)	Fog volume	Rain $\delta^{18}O$, δD (‰)	Rain volume	$\delta^{18}O$ enrich-ment*	δD enrich-ment*
1330	-3.4, -7	2120 mL	-3.6, -8	120 mL	0.7‰	10‰
1966	-2.8, -5	4820 mL	-2.6, -4	135 mL	2.9‰	21‰

both weeks: at Kailua (213 m altitude), there was light rainfall nearly every day, and at Haleakala Ranger station (2121 m altitude) there was no precipitation (*National Climatic Data Center).*

Streams

Streams in the study area were sampled for isotopic composition using several approaches. Two streams, Waikamoi and Palau-hulu, were accessible by road at higher altitudes, and were sampled at several altitudes and at different times to determine changes in isotopic composition along the stream. The Hana highway traverses the area from east to west between about 120-245 m above sea level and crosses all the streams. Streams that were accessible both at the highway and at sea level were sampled at each altitude for isotopic composition, specific conductance, and chloride to detect any evidence of deep ground water discharging to the stream. In a separate study by the U.S. Geological Survey *(Gingerich, 1999a)*, a series of discharge measurements were made along the length of selected streams within the study area to determine whether the streams were gaining ground water between measurement points. These measurements were made at times when the streams were assumed to be at baseflow conditions. Four of the streams were measured after this study began; in these streams, stable isotope samples were taken with each discharge measurement.

Six main irrigation ditch and tunnel systems carry water across the mountainside from east to west, with intakes to collect the water where they cross each of the streams (Figure 1). Most of the system is in the western part of the study area; the longest part extends 67 km east to Makapipi stream. At low flow conditions, all water is removed from the streams at the altitudes where the ditch systems intersect the streams. Therefore, the isotope samples downstream of diversions represent water discharging to the stream relatively near the sampling site.

Springs and Wells

Water emerges from the ground in innumerable places in this high-rainfall area, and it is often difficult to tell whether a spring is ephemeral or permanent. For this study, we generally sampled springs that were mapped and discussed in *Stearns and Macdonald (1942)*, springs marked on topographic maps, and springs that had associated water-collection systems, indicating that they were perennial. Springs that were sampled for this study fall into three general categories: 1) at or near sea level, representing discharge from the freshwater lens; 2) discharge from hill slopes or cliff sides above sea level, with small associated recharge areas; and 3) discharge occurring above sea level, sometimes at geologic contacts, associated with larger drainage areas. Most wells are located at low altitude in the western part of the area; eight were sampled during this study.

Recharge Altitude Calculations and Assumptions

The change in precipitation isotopic composition with altitude (Figure 3A) was used to identify sources of recharge to streams, springs and wells. Oxygen-18 was used for this analysis;

deuterium patterns were similar (see local meteoric water line in Figure 3B). To analyze patterns of ground water flow, the altitude at which precipitation $\delta^{18}O$ matched the ground- or surface water sample $\delta^{18}O$ was determined. This will be referred to as the recharge altitude. The actual altitude of each spring and stream sample site was then subtracted from the precipitation-derived recharge altitude. The discrepancy between actual altitude and estimated recharge altitude was plotted on maps to indicate sources of water to the streams along their length, and to help classify springs as being derived from shallow or deep ground water. Some samples had a lower apparent recharge altitude than their actual altitude, meaning that they had more enriched isotopic composition than the local volume-weighted average rainfall measured in our collectors. This was assumed to indicate a significant fog-drip component to the recharge for that stream segment or spring. When plotted relative to the local meteoric water line, these samples showed no evidence of evaporation. For ground water sites that were sampled more than once, the average isotopic composition was used to determine recharge altitude. For wells, the land surface altitude was used in the calculation rather than the depth of the screened interval. This simple match of precipitation $\delta^{18}O$ to sample $\delta^{18}O$ does not unequivocally identify the recharge altitude for the sample, for a number of reasons that are discussed in detail in later sections. Mixing of waters from several sources and altitudes may occur in the springs and wells, and certainly occurs in the streams. However, the approach facilitates comparison of samples within the study area.

RESULTS AND DISCUSSION

Isotope/Altitude Relations

The classic model for rain isotope depletion with increasing altitude involves a moist air mass rising and cooling. As condensation occurs and rain falls to the ground, the source vapor becomes increasingly depleted in the heavy isotopes, making subsequent rainfall more isotopically depleted *(Siegenthaler and Oeschger, 1980;* see *Gedzelman and Arnold, 1994*, for a complete summary). The orographic rainfall process in our study area (and many other areas) follows this model to some extent, but involves contact between the cloud and the land surface, which has not been discussed in the literature. Studies on hailstone formation (for example, *Federer et al, 1982; Jouzel et al., 1975)* show that isotope ratios for cloud water decrease with height (temperature) in the atmosphere. Rain droplet growth in Hawaiian clouds generally involves circulation and coalescence within the cloud, with most of the drop growth occurring in the tops of the clouds *(Takahashi, 1981)*. Different size rain drops will have different isotopic composition, even if formed at the same altitude, because the drops undergo equilibration with the surrounding vapor as they fall, and the larger drops will change composition more slowly than smaller drops *(Federer et al., 1982, Friedman et al., 1962)*. All these processes suggest that cloud droplets (fog and drizzle) sampled at the land surface would be isotopically enriched compared to larger rain drops sampled at the same time and location, if those drops originated at a higher altitude in the cloud.

In the rain shadows and areas above the inversion on the larger islands, the predominant source of rainfall is frontal systems or storms *(Schroeder, 1993)*. The trade-wind areas also receive some of this rainfall, subject to prevailing wind directions and mountain effects, as the fronts and tropical low pressure systems generally affect the entire island chain. Storm rain in the Hawaiian Islands is isotopically depleted compared to trade-wind-generated orographic precipitation *(Scholl et al., 1996)*, because the clouds extend much higher in the atmosphere, with colder temperatures, and because the systems are generally raining before they reach the islands. The water vapor in these systems can become more isotopically depleted, thereby producing rain that is more depleted than that produced by the warmer-temperature trade-wind processes, which are limited to altitudes below 3000 m by the trade-wind inversion.

Volume-weighted average isotopic composition of rainfall for all East Maui sites is given in Table 2, and Figure 3A shows $\delta^{18}O$

Table 2. Volume-weighted average stable isotope composition of rainfall, East Maui. The average is from four six-month cumulative samples taken over two years, except for P18, which was two samples over one year. Site locations shown in Figure 2. Abbreviations: TW = trade wind, HA = high altitude, RS = rain shadow, VWA = volume weighted average, σ = standard error.

Site Number	Altitude, m	Climate zone	VWA $\delta^{18}O$, ‰	σ $\delta^{18}O$	VWA δD, ‰	σ δD
P1	229	TW	-3.0	0.2	-8	1.5
P2	360	TW	-3.0	0.2	-9	0.5
P3	957	TW	-3.8	0.3	-14	2.1
P4	1295	TW	-4.1	0.4	-17	1.9
P5	1963	TW/HA	-5.7	0.9	-31	6.4
P6	2118	HA	-6.6	1.0	-39	8.2
P7	2591	HA	-8.2	1.5	-52	12
P8	2984	HA	-9.0	1.8	-58	14
P9	1829	RS	-7.0	1.2	-43	9.8
P10	1536	RS	-6.2	0.8	-37	5.5
P11	1265	RS	-5.6	1.0	-31	8.3
P12	963	RS	-5.6	0.6	-31	3.7
P13	542	RS	-5.1	0.6	-30	5.8
P14	305	RS	-4.7	0.7	-25	8.0
P15	136	RS	-4.7	1.5	-26	14
P16	2	RS	-4.4	1.4	-25	13
P17	412	TW	-3.0	0.3	-9	2.4
P18	168	TW	-2.8	0.01	-9	2.8

gradients with altitude for both East Maui and the southeast part of Hawaii Island (from *Scholl et al., 1996*). On both islands, there are distinct gradients for each microclimate type. The trade-wind and rain-shadow gradient pairs for each island are nearly parallel, but offset by about 2‰, with the rain-shadow gradients isotopically depleted, as explained above. The fact that the rain-shadow and trade-wind gradient pairs for each island have parallel slopes is probably due to the temperature lapse rate, which is the same in each microclimate, and which has a large effect on isotopic composition of rainfall.

The trade-wind $\delta^{18}O$ gradient on Hawaii was 0.16‰ per 100 m altitude. The analogous gradient for East Maui was similar but less pronounced, at 0.12‰ per 100 m, and was based on fewer samples extending only to 1295 m. The volume-weighted average rainfall for both trade-wind and high-altitude areas on East Maui was also about 0.4‰ more enriched than that on Hawaii, especially at higher altitudes (Figure 3A).

There are several possible explanations for the relative enrichment. Orographic rainfall occurs on the windward side of both islands, but the Maui study area faces directly northeast and has steeper topography than most of the Hawaii study area. Different cloud dynamics may cause a larger proportion of fog to occur against the mountain side on Maui. The distance between the area where clouds begin to form and the mountain side is shorter on Maui than on Hawaii, so that isotopic depletion of the water vapor due to loss of raindrops from the cloud may not occur to the extent it does on Hawaii. Another important factor is water vapor from transpiration on the forested mountain slopes, this may add a relatively isotopically enriched component to the cloud vapor; as windward Maui has more forest cover than most of the study area on Hawaii Island.

The rain-shadow data for Maui and Hawaii are very similar, with the exception of the sites at 1265 and 1536 m altitude. These sites were in a documented fog belt on leeward East Maui *(Giambelluca and Nullet, 1991)*, and it appears that those collectors contained some fog water as well as storm rain. The relative enrichment in the highest-altitude collectors on Maui suggests the trade-wind clouds frequently extend to the altitude of our highest collector near Haleakala summit (2984 m). A fog collector at 3415 m at Mauna Loa Observatory on the Island of Hawaii measured an annual average of 186 mm of fog water (amounting to 44% of rainfall at the site), suggesting that fog drip is significant at these altitudes in the Hawaiian Islands *(Juvik and Ekern, 1978)*.

The isotopic composition of the fog drip samples in this study are shown in Figure 3B and listed in Table 1. These measurements are short-term samples, but show that the precipitation caught by the fog collectors, presumably fog and drizzle, was significantly isotopically enriched in comparison to the volume-weighted average rainfall at the same altitude. The higher-altitude fog sample is more isotopically enriched than the lower altitude sample, consistent with greater isotopic fractionation as water vapor condenses at cooler temperatures, although the comparison would be better if both samples had been collected at the same time.

The volume-weighted average isotopic compositions for the trade-wind area gradient included unknown proportions of fog, trade-wind-generated rain, and storm rain. The amount of fog collected with the funnel collectors almost certainly does not approximate the proportion of fog that must be intercepted by the trees and other vegetation of the cloud forest. The ratio of fog to rainfall has not been published for this area of Maui, but *Juvik and Ekern (1978)* in a study on Hawaii Island, found fog to amount to 30 to 68% of rainfall annually, with fog drip exceeding rainfall during spring and summer months at one station (Figure 4).

If fog is a significant component of the water budget, this complicates the interpretation of ground water source using stable isotopes. Since fog drip appears to be isotopically enriched compared to average rain at the same altitude, recharge by a mixture of fog drip and rain would lead to a lower recharge-altitude estimate for a

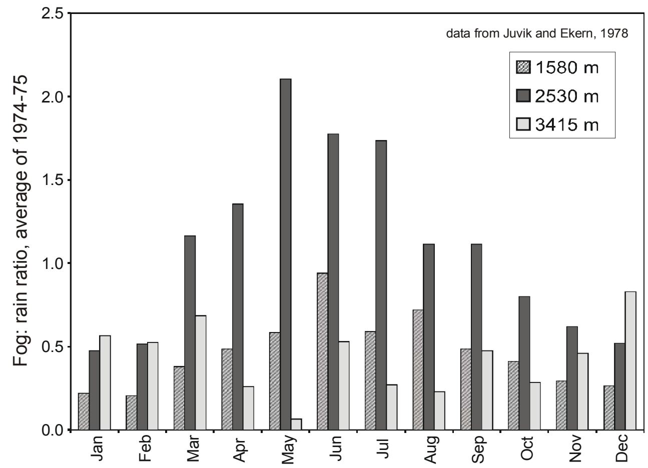

Figure 4. Average monthly ratios of fog to rainfall measured at stations at three altitudes on the east-northeast slope of Mauna Loa, Hawaii in 1974 and 1975. Graph is from data published in Table 3 of *Juvik and Ekern* (1978).

ground water sample. Figure 4 shows that the proportions of fog and rain in the total precipitation measured at a site change seasonally. For northern Chile, *Aravena et al., (1989)* found ground water isotopic composition was similar to rainwater, while leaf water reflected fog drip uptake by the plants. *Ingraham and Matthews (1995)* found that ground water recharge in northern California appeared to be predominantly rain, with some fog-drip input. These studies indicate that our funnel collection method may approximate the isotopic composition of recharge to the deeper ground water system, but many new questions have been raised about the hydrologic processes in the study area and their effect on isotope signatures, and further work needs to be done. For the recharge analysis presented here, the samples with a significant fog-drip source or a very high recharge altitude will stand out, but samples that may actually be mixtures of fog and rain are categorized as local recharge.

Source and Flow Path Analysis

To show differences in ground- and surface water recharge sources, the discrepancy between actual altitude and apparent recharge altitude for each sample site is plotted on the area maps in Figures 5 (ground water) and 6 (surface water). If sample composition was isotopically enriched compared to local volume-weighted

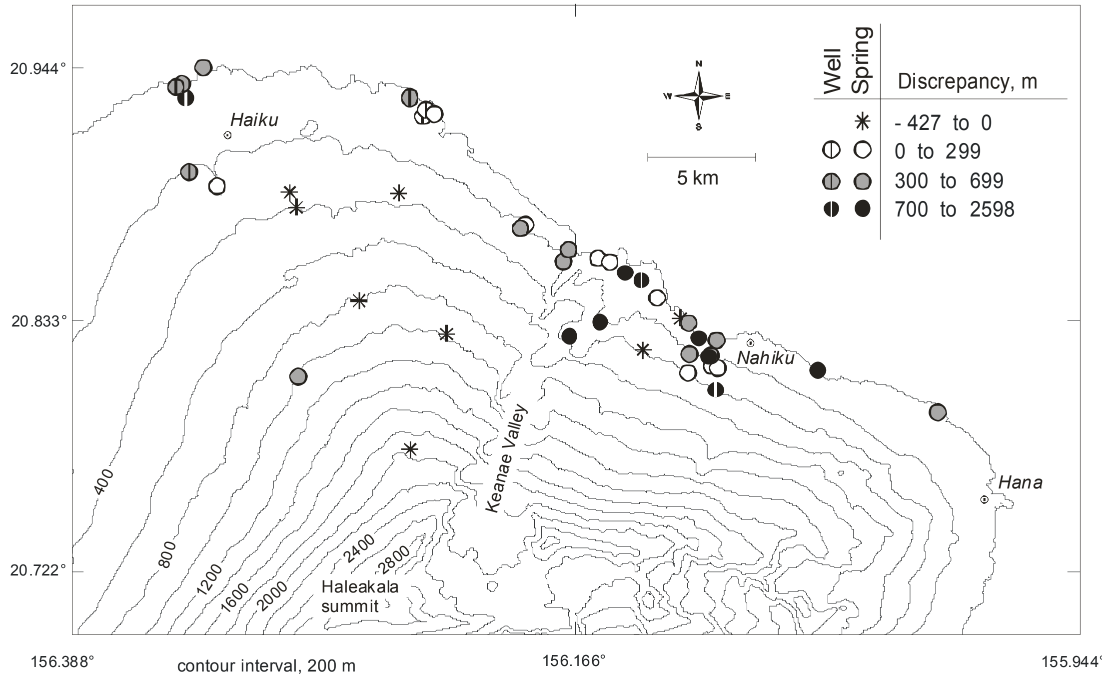

Figure 5. Discrepancy between $\delta^{18}O$ – derived recharge altitude and actual altitude of spring or well, in meters. Average values are shown for sites that were sampled repeatedly.

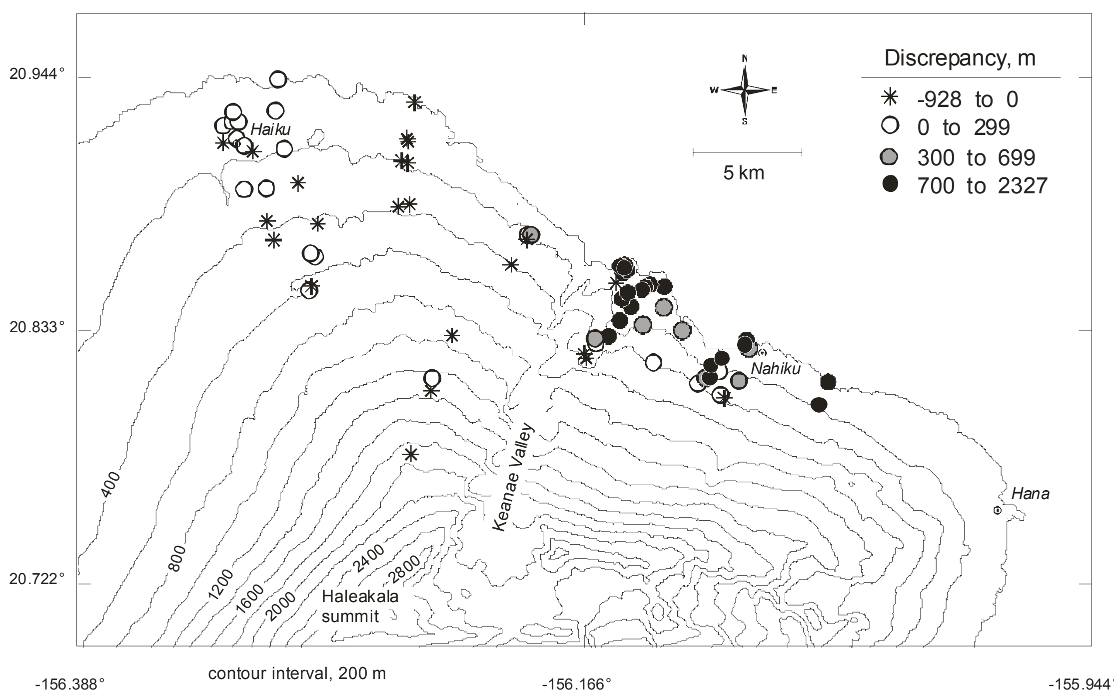

Figure 6. Discrepancy between $\delta^{18}O$ – derived recharge altitude and actual altitude of stream sample, in meters.

average precipitation (negative discrepancy), fog drip was assumed to contribute substantially to recharge for the sampled feature. The main fog drip zone has been estimated to be between 1000-1900 meters altitude on the windward slope of East Maui *(Kitayama and Mueller-Dombois, 1994)*, although fog is probably present from about 600 m up to Haleakala summit at 3055 m, *(Giambelluca and Nullet, 1991; Juvik and Ekern, 1978)*. Springs with negative discrepancy were above 34 m in altitude. Stream samples with negative discrepancy were obtained at altitudes from 5 m to 1966 m. The samples with fog-drip isotopic signature were collected over several years, and in all seasons, suggesting that fog-drip recharge commonly contributes to shallow ground water discharge in streams and small springs throughout this area.

If sample composition matched precipitation composition within –0.35‰ (+299 m altitude), either local recharge or a mixture of fog drip and higher altitude rain recharge was inferred. If the altitude was more than 700 m above the sample site (>0.8‰ more depleted in ^{18}O than local precipitation), the existence of a larger-scale ground water system could be inferred, with the flow path between recharge site and sampling site relatively deep within the northeast slope of the volcano. Features with the largest positive discrepancy between recharge altitude and actual altitude were generally coastal springs, wells drilled to sea level, and deep ground water-fed streams.

Time Series for Selected Locations

Several springs, wells and streams were sampled repeatedly during the period of study, September 1995 to May 1999 (Table 3). Variables affecting the isotopic composition of streams, in particular, included the antecedent rainfall and how much water the irrigation ditch system was taking from the streams. Temporal variability in springs depends on the size of the recharge area for the spring, the distance the water travels from source to outlet, and variability in the precipitation source. Two small springs at high altitude (Waihou, 1021 m, and Hosmer's Grove, 1987 m, Table 3) had the most variable isotopic composition. The predominant recharge sources for these high-altitude springs may be storm rain and fog drip, which have strongly contrasting isotopic signatures. This has implications for isotope hydrology studies where springs are used to determine the isotope/altitude gradient for an area. Perennial springs are generally assumed to provide a long-term average isotopic composition of local recharge. On the cloudy upper mountain slopes of East Maui, the isotopic composition of the springs is extremely variable, and multiple samples over a time period sufficient to cover all types of recharge events would be required to obtain a meaningful average.

In contrast, the lower-altitude trade-wind rains (below cloud base) seem to be very consistent in isotopic composition (see error (σ) values in Table 2), so that the isotopic signature

Table 3. Temporal variation in some springs and streams sampled repeatedly during the study.

Location	Sep '95		Feb '96		Sep '96		Mar '97		Sep '97		May '99	
	δD	$\delta^{18}O$	δD	$\delta^{18}O$	δD	$\delta^{18}O$	δD	$\delta^{18}O$	δD	$\delta^{18}O$	δD	$\delta^{18}O$
Waihou Spring	-24	-4.7	-17	-4.1	-22	-4.5	-26	-4.9	-23	-4.7		
Hosmer's Grove spring	-25	-4.9	-22	-5.0	-31	-5.8	-33	-6.3	-28	-5.3		
Nuaailua roadcut			-9	-2.8	-6	-2.8	-7	-2.8	-8	-2.8		
Big Spring	-22	-5.0			-23	-4.8						
Ohia Spring			-22	-4.6	-22	-4.7	-23	-4.8	-21	-4.4		
Palauhulu str. At 305 m									-9	-3.0	-4	-2.5
Palauhulu str. At 23 m							-20	-4.5	-18	-4.2	-16	-4.1
Makapipi str. at mouth							-19	-4.3			-12	-3.4

of a small locally-recharged spring at low altitude (Nuaailua roadcut, 73 m) was effectively constant over a two year time period. Also shown in Table 3 are two large low-altitude springs (Big Spring, 240 m, and Ohia Spring, 61 m), which have effectively constant composition and isotopic signatures indicating recharge from about 1700 m altitude. These springs represent a deep ground water system with a longer, more well-mixed flow path.

Palauhulu Stream is in the Keanae Valley (Figure 1). The difference in isotopic composition between the highest altitude sampled on Palauhulu Stream (305 m) and the lowest (23 m) illustrates that the stream is gaining 'deep' ground water along that reach (Table 3). The water in the stream at the 23 m sampling point varied little between sampling periods. In contrast, Makapipi Stream had significantly different isotopic composition on the two occasions it was sampled, reflecting differences in antecedent rainfall mixing with the baseflow.

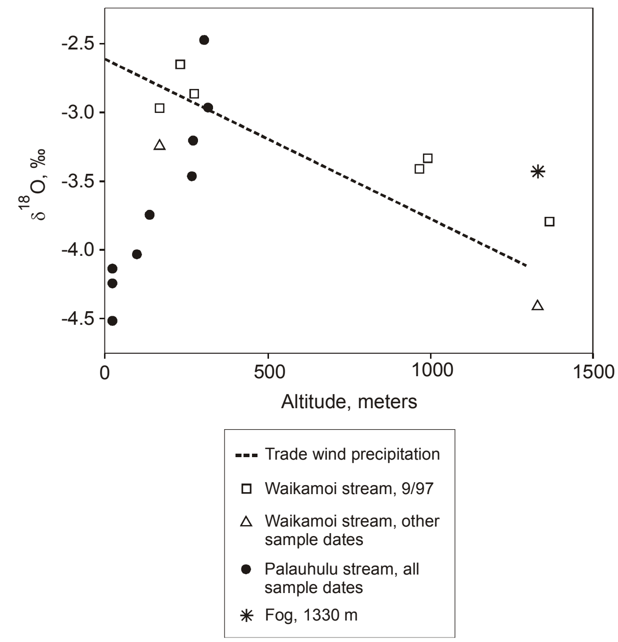

Figure 7. $\delta^{18}O$ values of samples from Waikamoi and Palauhulu streams below 1500 m altitude, showing fog drip and deep ground water sources for streamflow.

Sources of Streamflow

A comparison of stream and precipitation isotopic composition illustrates how stable isotopes can be used to determine the sources of water to the streams (Figure 7). Waikamoi stream had a strong fog-drip signature at higher altitudes during September 1997, as indicated by the stream water isotopic composition that plots on the enriched side of the precipitation/altitude line for the trade-wind area. In contrast, a February 1996 sample from the reservoir on the stream at 1329 m had a composition that plotted below the precipitation line, suggesting a rainfall and/or shallow ground water source. Two samples taken at different times at the lowest altitude have isotopic signatures that plot on the isotopically depleted side of the precipitation /altitude line, suggesting a contribution of ground water from farther upslope.

Palauhulu stream shows a different pattern, that of a stream gaining isotopically depleted ground water as it loses altitude. Samples from March 1997, September 1997, and May 1999 are plotted in Figure 7. The highest altitude samples (305 m) plot on or above the precipitation line, indicating that precipitation and fog drip contributes to streamflow. At lower altitudes, the $\delta^{18}O$ composition of stream samples becomes increasingly depleted, indicating that the stream is fed by ground water that has been recharged at a significantly higher altitude.

Interpretation of Regional Hydrology – Isotope Evidence

Maliko Gulch to Keanae Valley

Gingerich (1999b) hypothesizes that the ground water system west of Keanae Valley consists of a freshwater-lens aquifer in the higher-permeability Honomanu Basalt near sea level and perched water in the overlying lower-permeability Kula Volcanics. Evidence includes observations that streams flow all the way to the ocean when they flow on the Kula Volcanics, whereas streams that have incised the underlying high-permeability Honomanu Basalt near the coast go dry.

Although areal coverage of samples, especially near the coast, is limited, the isotopic data support the hypothesis of a dual system. The majority of stream samples west of Keanae Valley have recharge altitude discrepancies of 200 m or less (Figure 6), and the relatively large number of negative discrepancies suggests that fog drip contributes substantially to stream flow. Stream baseflow appears to be local, shallow ground water, probably a mixture of rainfall and fog drip. Many of the higher altitude springs in this area also show a fog drip or local ground water origin (Figure 5). The westernmost springs that were sampled in and near Maliko Gulch are an exception. A possible reason for this is that they are located near the transition from windward trade-wind climate to leeward storm-dominated climate; the shallow ground water would be more isotopically depleted if the area received a larger proportion of storm rainfall than further east.

Six wells were sampled west of Keanae Valley. Only the wells tapping the freshwater lens near sea level show recharge altitudes as high as those found in Keanae Valley and further to the east. Wells completed above sea level encounter local ground water, as would be typical for a perched water body.

Keanae Valley

The Keanae Valley is a large erosional feature, about 3 km wide at the coast, that extends from the ocean to Haleakala crater (Figure 1). The lower portion was filled with alluvial sediments following submergence during an episode of higher sea level, then late-stage eruptions produced lava flows that covered the alluvium and partially filled the valley *(Stearns and Macdonald, 1942)*. *Gingerich (1999a)* provides hydrological evidence that the area to the east of Keanae Valley has a body of high-level ground water such that the rocks are fully saturated to hundreds of meters above sea level, in direct contrast to previous conceptual models of the configuration of Hawaiian aquifers.

Ground water and surface waters sampled within Keanae Valley were very different in isotopic composition from those in the western part of the study area. Three streams flow through the valley (Piinaau, Palauhulu, and Waiokamilo), and four large named perennial springs and a number of unnamed springs discharge there. Six springs, a well, and the three streams were sampled during this study. Most of the water samples had estimated recharge altitudes greater than 700 m above their altitude.

The Koolau ditch/tunnel system runs along the slope through the Keanae Valley at about 400 m altitude and has intakes at all three streams. Therefore all of the flow in the valley streams enters below 400 m, except during storm-runoff conditions. Palauhulu and Waiokamilo streams appear to be predominantly spring-fed. Palauhulu stream (Figure 7) and Piinaau stream acquire progressively more isotopically depleted water as they flow toward the ocean. Similarly, springs in the Keanae valley (data not shown) have $\delta^{18}O$ composition of –3.85‰ at 220 and 300 m, and –4.7‰ at 61 m. Most springs and the well that were sampled in Keanae Valley have isotopic signatures that match precipitation from 300 to 1761 m altitude, a lateral distance of as much as 11 km upslope. *Stearns and Macdonald (1942)* noted that a test hole drilled at 378 m altitude in the valley had a water level 280.6 m above sea level. The spring discharging in the valley near that altitude (300 m) had a deep ground water isotopic signature. The pattern of isotopic signature becoming more depleted with decreasing altitude that was observed in two of the three streams is consistent with a fully saturated ground water system, with water levels much higher than a typical freshwater lens in high-permeability basalt.

East of Keanae Valley

Gingerich (1999a) concludes that there is a fully saturated ground water system from Keanae Valley east to Makapipi stream. Evidence for the high-level ground water includes seventy-six test holes that were drilled in the 1930s and 40s in the Nahiku area, which contained water at 104 to 447 m above sea level *(Meyer, 2000)*. The Kuhiwa well, at land surface altitude of 426 m, has a water level 343 m above sea level. Most of the streams are perennial around 400 m altitude.

Samples for isotopic analysis were taken at altitudes near or below 400 m, since access to higher altitudes in this area is limited. Although there is a mixture of isotopic signatures, the most isotopically depleted samples in the entire study area, having recharge altitudes >1000 m above the site, are from streams, springs and wells east of Keanae valley. The Honomanu lavas are reported to be lower-permeability and more massive in this area than to the west *(Stearns and Macdonald, 1942; Gingerich, 1999a)*, possibly contributing to the relatively high water levels.

In this study, deep ground water (recharge discrepancy >700 m) was found discharging in streams and springs at and below 305 m altitude. The isotopic signature and the water level in the Kuhiwa well indicate that the high-level ground water body extends to at least 343 m. Sampling perennial streams along their length during a period of baseflow might help pinpoint exactly where the deep ground water discharges, and the extent of the anomalously high ground water levels.

SUMMARY

Stable isotopes of water were used to constrain ground water and stream water sources on the windward slope of East Maui. Numerous stream and high-altitude spring samples that were isotopically enriched relative to volume-weighted average local rainfall suggest that fog drip is an important component of the water budget. Limited data suggest that rainfall and fog components of precipitation in the area can be distinguished by their isotopic signature, but more work needs to be done. The traditional funnel-type rain collectors used in this study probably under-represented the fog contribution to precipitation isotope signature. This lends uncertainty to the interpretation of recharge altitude and source for ground water samples in the study area, however, it is unknown whether fog drip contributes much to deep ground water recharge. A detailed study of hydrologic processes in the cloud forest, investigating the relative proportions of fog drip and rainfall and their role in stream baseflow and deep aquifer recharge, would help answer some of the questions generated in this work.

Isotopic signatures of ground water and stream flow allowed insight into the structure of the regional aquifer system, identifying areas with a high water table and deep ground water discharge where there was insufficient evidence to make conclusions based on the hydrogeology alone. The results suggest a vertically extensive body of ground water in the Keanae valley up to about 300 m altitude. The deep-ground water signature of springs and a well east of Keanae valley indicates that this ground water body exists in that area also, but its horizontal and vertical extent is unknown. Isotopic evidence supports the concept of a perched water body in the Kula Volcanics above a freshwater lens in the area west of Keanae Valley. These results will help in predicting the effects of ground water development on stream flow in the area.

Supplementary Material:

Tables containing all data for this study (sample dates, location, elevation, stable isotope composition) are available upon request from the first author, mascholl@usgs.gov, or at:
http://water.usgs.gov/nrp/proj.bib/
Hawaii/east_maui.htm

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