A STUDY OF THE GROUND-WATER CONDITIONS IN NORTH AND SOUTH KONA AND SOUTH KOHALA DISTRICTS ISLAND OF HAWAII, 1991-2002

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To All Interested Parties:

The Commission on Water Resource Management (CWRM) is pleased to present the attached report: A Study of the Ground-Water Conditions in North and South Kona and South Kohala Districts, Island of Hawaii, 1991-2002. This study on the ground-water conditions in West Hawaii from 1991 to 2002 is ongoing. The initial impetus for collecting ground-water data in West Hawaii was due to fierce competition for the resource in the early 1990's, and the role CWRM played to prevent competition from becoming major disputes. When trying to mediate between landowners, developers, and other water purveyors, it became clear that basic water level data was not available. This study presents over ten years of baseline water level data. New knowledge about the high-level and basal resources is presented in this report.

During the past ten years, many wells were drilled in North and South Kona and South Kohala Districts of the Big Island. Private landowners, public utilities, and the State invested large sums of money to drill these wells for the economic benefit of the island and the State of Hawaii. CWRM is grateful for the cooperation shown by these entities in allowing access to their wells for water level data collection and sampling purposes. Collaboration with private consultants and scientists from the U. S. Geological Survey's Hawaii Volcano Observatory added new geological information presented in this report.

I hope, as Chairperson of the Commission on Water Resource Management, that interested parties will make good use of the data collected. This study shows that the collaborative effort undertaken by CWRM staff, well owners, developers, and private consultants can produce a useful "product."

PETER T. YOUNG, Chairperson
Commission on Water Resource Management

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EXECUTIVE SUMMARY

Over the past 15 years, West Hawaii has experienced tremendous growth in population, resort development, and reliance on the available ground-water resources. In the early 1990's high-level ground water was encountered by drilling above 1,600 ft., mean sea level (msl). Exploitation of this new resource as well as the basal aquifer resource began in earnest. The Commission on Water Resource Management (CWRM) became concerned over proper planning, well placement, and associated well interference. CWRM facilitated meetings between the landowners, developers, and consultants to bring about orderly development and to prevent designation of the area due to disputes among the parties. Two groups were formed. The Hualalai Users Group met to discuss mutual problems associated with development in Kailua-Kona and the North Kona District; the Lalamilo Users Group worked to alleviate problems encountered in the South Kohala District.

It became apparent that knowledge of the resource was based upon older basal wells drilled for the county water supply and limited knowledge of the new high-level resource. There were no baseline ground-water data available that could be used to predict basal and high-level aquifer behavior. Hence, CWRM undertook the task, with the help and partnership of the private sector, to collect and analyze ground-water data from West Hawaii.

Major findings and conclusions are based upon 171 individual water level measurements in the high-level wells and 636 measurements in the basal wells. These findings include the following:

1. The data strongly suggest a slow decline of water levels in some of the high-level wells and an apparent relationship to water level decline and climatic conditions as recorded in the Lanihau and Huehue Ranch rain gages. Future wells drilled into this resource should be used, prior to pump installation, as observation wells to verify the trends documented in this report.

2. The data suggest that the high-level wells tap interconnected, though bounded, aquifers whose rate of water level decline is inversely proportional to its volume. Future well drilling for high-level potable sources must include accurate, well-designed aquifer tests that will aid in the determination of geologic boundaries to provide information on the geometry of the aquifer.

3. The data suggest that there may be more than geological mechanism that created the high-level aquifer.

4. The data suggest that there is a water level pattern observed in the high-level wells with Keopu being the “drain” for the ground-water flow system. The ground-water flux south of Keopu is to the north, and north of Keopu, the ground-water flow is to the south.

5. Some high-level wells do exhibit quasi-stable water levels, and show little variation over time. Use of long-term water level transducers in these wells should continue in conjunction with long-term water level transducers in those wells that show water level decline. Real time correlation between water levels in the wells with climatic conditions measured at Lanihau Rain Gage will provide better insight into the behavior of the potable high-level aquifers.

6. The data suggest the influence of climate over long-term trends in the basal aquifers.

7. The strong correlation between well pairs will aid in predicting a water level if only one of the wells can be measured.

8. The data suggest the variability of the ground-water flow direction in a shallow basal lens system, as can be seen at the West Hawaii Landfill, is translatable to other areas.

9. The low ground-water gradients suggest a highly permeable basal coastal aquifer where basaltic lavas comprise the aquifer, and this finding is supported by tidal analysis. The composition of the lava flows determines its permeability, and in turn, the ground-water gradient.

10. These data will become calibration targets for future numerical and analytical ground-water models and will aid in the site selection for new wells.

1. Introduction

During the 1980's through the early 1990's Kailua-Kona experienced tremendous growth. Growth continues to this day; however, associated with the activities of the early 1990's was the high demand on water supplies and competition among large landowners/developers for new sources of supply. As wells were drilled, new and interesting geological and hydrological information began to emerge that spurred additional wells at higher elevations, and at greater cost. Because of competition for well site locations and concerns by the Commission on Water Resource Management (CWRM) about proper planning, well placement, and associated problems of well interference, CWRM began a series of meetings in North Kona and South Kohala Districts among the major landowners, developers, engineers, and hydrologic consultants in order to come to agreement as to the proper development of the ground-water resource. The two ad hoc groups were formed. The Hualalai Users Group focused on problems near Kailua-Kona and the North Kona District, while the Lalamilo Users Group centered on problems related to the South Kohala District. These meetings provided an avenue to diffuse any disputes and to forestall any designation of the West Hawaii region as a ground-water management area. As these meetings took place, it became abundantly clear that good baseline ground-water data were sparse and that major decisions were not made using a "complete data-set," but rather by incomplete knowledge of the resource. It was for this reason that CWRM started the ground-water monitoring program in West Hawaii.

Since 1991 ground-water elevation measurements have been taken in 40 public and private wells and test holes throughout the North and South Kona and South Kohala Districts of West Hawaii. The regulatory scheme defined by the State Water Resources Protection Plan Vol. II (1992), and adopted by the CWRM, includes wells located in the Kealakekua Aquifer System of the Southwest Mauna Loa Sector, the Keauhou and Kiholo Aquifer Systems of the Hualalai Sector, the Anaehoomalu Aquifer System of the Northwest Mauna Loa Sector, and the Waimea Aquifer System of the West Mauna Kea Sector (Geo. A. L. Yuen and Assoc., 1992).

CWRM staff performs almost all measurements. However, the U. S. Geological Survey (USGS) takes additional water level measurements as part of the cooperative agreement with CWRM. Since data collection began some wells were either dropped from the survey due to pump installation, to loss of access, or to vandalism. Because of these changes, newly drilled wells are incorporated into the ground-water data collection network to replace those that are no longer available giving a continued broad view of ground-water conditions in West Hawaii. Forty wells are in the study, and about 25 wells at any one time are measured quarterly over a period of several days. These wells are considered primary; that is, their accessibility and location are important to the construction of water level maps and other hydrological studies. The majority tap the basal aquifer, and nine are drilled into high-level aquifers.

As stated above, measuring ground-water elevations in Kona began in earnest when new water wells drilled at altitudes greater than 1,600 ft. reported water levels between 40 and 490 ft. above mean sea level (msl) in North and South Kona. The potential for developing this new high-level resource, coupled with an increasing demand for water from existing basal sources and the impending development of new private basal wells, created an impetus for collecting baseline water level data. The resulting baseline data, collected over the past 11 years, are a valuable tool to establish ground-water trends, to construct and calibrate numerical ground-water models, and in the future, to compare ground-water conditions against the baseline.

<u>2. List of Wells Monitored Within the Network</u>

Table 1 presents a summary of all wells and test holes that have been incorporated into the West Hawaii water level network. Table 1 presents all of the reference benchmarks (measuring points) used to determine water level elevations. However, because of the great distances between wells, the benchmarks are not surveyed or tied to each other, but instead are leveled in from state highway monuments and USGS benchmarks where available. Because of that, even though water level elevations are referenced to mean sea level, and are accurate to the nearest 0.01 ft., the measurements between the wells are not absolute, but relative to the measuring point. Nevertheless, climatic changes and response to rainfall recharge are seen in all wells measured over time.

Table 1. List of wells in the ground-water network.

Well Name	WELL No.	Reference Benchmark (ft.,msl)	Geology	Hydrology	Measurement Period
Kealakekua[1]	3155-01	1751.93	Mauna Loa	high-level	1991-2000
USGS Kainaliu[1]	3255-01	1660±	Mauna Loa	high-level	1991-1993
Kainaliu Test[2]	3255-02	1541.46	Mauna Loa	high-level	1993-1994
Keauhou-Kam 2	3355-01	1619.57	Hualalai	high-level	1993-2002
Keauhou-Kam 3[3]	3355-02	1664.01	Hualalai	high-level	1993-1997
Keauhou-Kam 4[2]	3355-03	1650.52	Hualalai	high-level	1994
Keauhou B	3456-01	1018.93	Hualalai	basal	1992-1996
Keauhou A	3457-02	722.99	Hualalai	basal	1993-2002
Kahaluu Deep Monitor[4]	3457-04	310.83	Hualalai	basal	2001-2002
Pahoehoe	3657-02	1148.54	Hualalai	basal	1993-1997
Keopu Deep Monitor [4]	3858-01	737.91	Hualalai	basal (?)	2001-2002
USGS Komo[4]	3957-02	1601.22	Hualalai	high-level	1991-2002
Honokohau	4158-02	1677.75	Hualalai	high-level	1992-1995
Kaloko Irr. 1[5]	4160-01	566.86	Hualalai	basal	1992-1993
Kaloko Irr. 2[3]	4160-02	544.00	Hualalai	basal	1993-1997
Hualalai	4258-03	1681.88	Hualalai	high-level	1993-2002
Ooma Test	4262-01	90.50	Hualalai	basal	1993-2002
Kalaoa Irr.	4360-01	680.80	Hualalai	basal	1992-2002
Kau 1 (Kohanaiki)	4458-01	1799.85	Hualalai	basal	1991-2001
Kau 2 (Kohanaiki)	4458-02	1800.99	Hualalai	Basal	1991-2002
Huehue 1	4559-01	1578.84	Hualalai	basal	1993-2002
Huehue 3[3,6]	4558-01	1517.40	Hualalai	basal	1992-1993
Huehue 5	4558-02	1529.12	Hualalai	high-level	1997-2002
Kaupulehu 1	4658-01	1344.41	Hualalai	basal	1992-1996
Kaupulehu Irr. 1	4757-01	849.59	Hualalai	basal	1992-1996

Well Name	WELL No.	Reference Benchmark (ft.,msl)	Geology	Hydrology	Measurement Period
Kukio Irr. 1	4759-01	592.77	Hualalai	basal	1992-2000
Kukio Irr. 2	4759-02	553.10	Hualalai	Basal	1992-2000
Kukio Irr. 3	4759-03	595.40	Hualalai	basal	1992-2000
Kiholo[7]	4953-01	932.48	Hualalai	basal	1993-1999
Puu Anahulu[5]	5347-01	1520.60	Mauna Loa (?)	basal	1996-2002
West Hawaii Landfill MW 1	5352	232.19	Mauna Loa (?)	basal	1996-2002
West Hawaii Landfill MW 2	5352	214.07	Mauna Loa (?)	basal	1996-2002
West Hawaii Landfill MW 3	5352	153.62	Mauna Loa (?)	basal	1996-2002
Waikoloa 3	5546-02	1218.23	Mauna Kea	basal	1993-1996
Waikoloa Irr. 4	5552-01	95.48	Mauna Loa	basal	1993-2002
Waikoloa Irr. 5	5551-01	126.03	Mauna Loa	basal	1993-2002
Waikoloa MLR 1	5846-01	1181.14	Mauna Kea	basal	1993-1997
Waikoloa MLR 2[8]	5849-02	NA	Mauna Kea	basal	1993
Ouli 1	6046-01	1303.80	Mauna Kea	basal	1993-2002
Ouli 2	6146-01	1311.02	Mauna Kea	basal	1993-2002

[1]Water level measurement performed by the USGS. See: http://hi.water.usgs.gov/recent/4953-01.html
[2]Excessive oil from pump in the well.
[3]Acess no longer available.
[4]Handar data logger installed for continuous water level measurements.
[5]Well vandalized.
[6]Water level measurements using an airline.
[7]USGS began measuring continuously since the end of 1999.
[8]Only one water level measured after well was drilled due to lack of credible reference benchmark.

Figure 1 is a folded map locating the wells presented in Table 1 within aquifer system boundaries. As Figure 1 shows, the majority of wells are located in the Keauhou and Kiholo Aquifer Systems. These wells are located at regular intervals, allowing for mapping ground-water contours with some confidence.

Nine network wells occur in clusters further north of the Kiholo Aquifer System. Because of this clustering, large areas of no data exist, making ground-water mapping more conjectural. Distances between these clustered wells are also much greater than in the Kailua-Kona to Keauhou region.

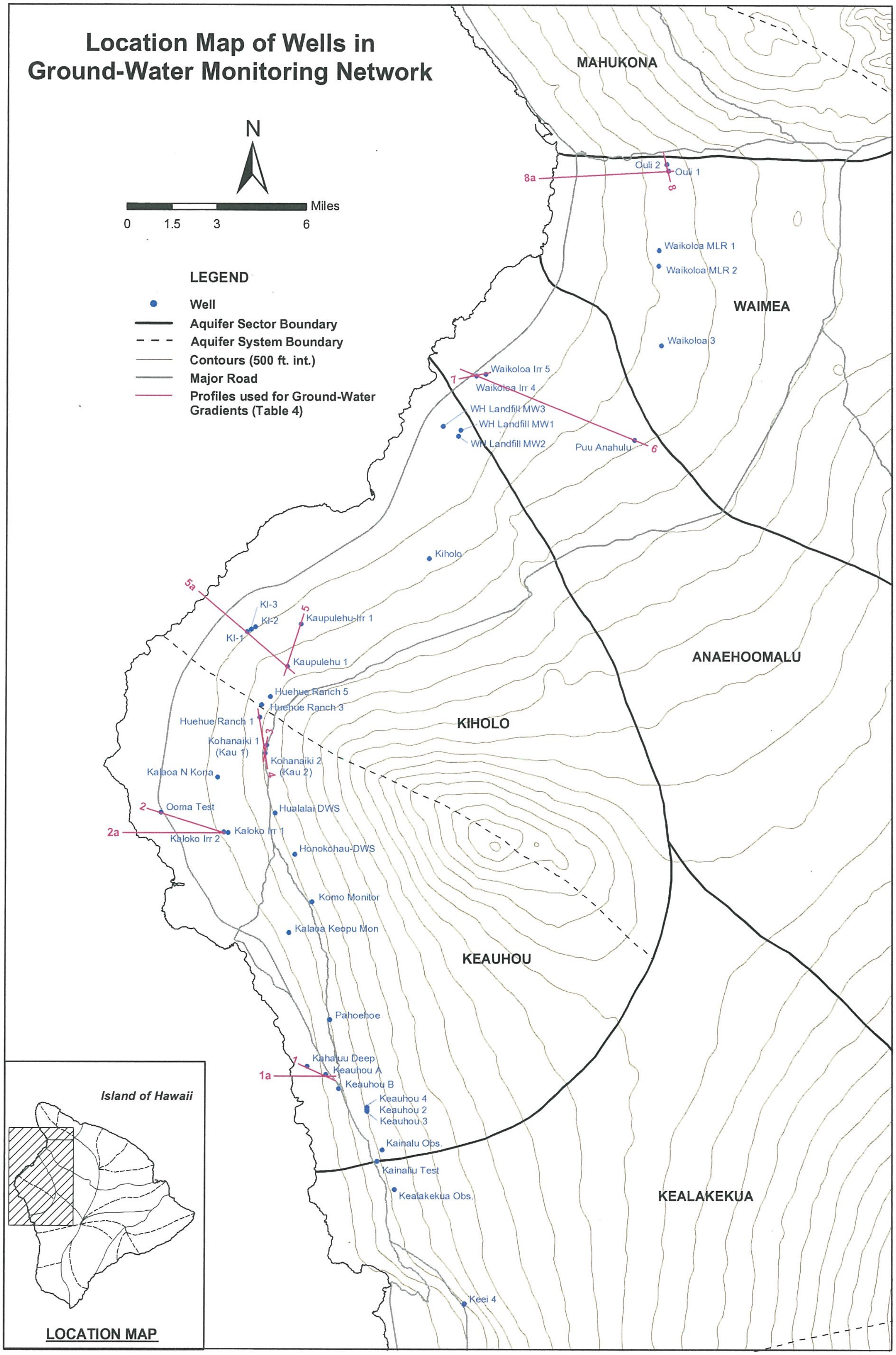

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Figure 1

Further complicating the picture are the geologic units that the wells penetrate. Most of the wells in the network are drilled into Hualalai lavas. There are a few wells south of Keauhou penetrating Mauna Loa lavas, as are some wells north of Kailua-Kona that are located in the Anaehoomalu Aquifer System. Other wells drilled in the Waimea Aquifer System enter Mauna Kea lavas. The Ouli Wells (6045-01 and 6046-01), though situated on Mauna Kea lava, may actually penetrate into Kohala lavas at depth. Tom Nance Water Resource Engineering (2000, Figure 7), projects the sea level contact of the Kohala volcano with the younger Mauna Kea lavas and shows that the Ouli Wells could be penetrating Kohala lava flows with bottom elevations of –97± ft., msl and –50± ft., msl, for Ouli Well 1 (6045-01) and Ouli Well 2 (6046-01), respectively (TNWRE, 2000, Table 3).

3. Geology

The surficial geology of West Hawaii has been well mapped (Stearns and Macdonald, 1946; Moore and Clague, 1991; Wolfe and Morris, 1996), but the subsurface geology has only recently been studied in more detail, partly from new wells drilled throughout the region, partly from offshore submarine mapping by the USGS, and partly from geophysical studies. As will be shown, the subsurface geology controls the movement and occurrence of ground water in West Hawaii.

Hualalai, Mauna Loa, Mauna Kea, and Kohala shield volcanoes comprise the study area. The aquifer systems generally coincide with the surface expression of the geological contacts between the volcanoes. Figure 1 shows that some wells near the aquifer system boundaries may in fact be penetrating lavas from the adjoining volcano. For example, the Kainaliu Test Well is near the contact between Mauna Loa and Hualalai, and is more likely to be situated in Mauna Loa lavas (Stearns and Macdonald, 1946; Wolfe and Morris, 1996). Mauna Loa and Hualalai are contemporaneous, therefore, interbedding of lava flows probably occur at depth so that it is possible for lavas of Mauna Loa composition to be the water bearing rocks north of the surface contact.

Generally, the composition of the lava determines its permeability. Thin-bedded permeable basaltic pahoehoe and aa lava flows from Mauna Loa and Hualalai volcanoes form much of West Hawaii. The geochemical composition of basalt is such that it is low in silica and its alkali constituents (sodium and potassium), and high in iron, magnesium, and calcium. Basaltic pahoehoe lavas are fluid (even though the viscosity of the most fluid basalt lava flow is one million times greater than water) when erupted, they change into aa as the flow moves down-slope. Because of the viscosity of basalt, the lava flows tend to be comparatively thin-bedded and flow great distances. An example is the 1859 lava flow from Mauna Loa that extends almost 29 miles from 9,200 ft. on Mauna Loa's northwestern flank to the ocean near Kiholo Bay. In contrast, thicker, denser, and less permeable hawaiite (andesitic) lava flows from Mauna Kea compose much of the Waimea Aquifer System. Chemically, hawaiite is about equal in its silica content to basalt; however, the total alkali content of sodium and potassium is greater (Macdonald, 1968). Hawaiite lava flows tend to be thicker and are usually denser (fewer gas bubbles or vesicles) than basalt.

Geologic logs for recently drilled wells from Kaupulehu in the north to the DWS' Hualalai well (4258-03) in the south indicate the presence of trachyte lava. Trachyte ash was encountered farther south in the Keopu-Haseko well (3957-01) at a depth of 1,330± ft., msl (Cousens and others, 2003). Trachyte compositionally has a much greater amount of silica. The total alkali content is more than double that of hawaiite (Macdonald, 1968). These lavas are extremely viscous so that the flows tend to be thick and massive and impermeable. It is unknown at this time if the trachyte lava represents one massive flow or several flows, but in this paper they will be considered as several flows. Previously, only Puu Waawaa and Puu Anahulu were mapped as trachyte (Stearns and Macdonald, 1946).

Table 2 presents the top and bottom elevations for the trachyte flows encountered during drilling. These flows, presumably dipping seaward, could influence ground-water flow due to their morphological characteristics and affect water level elevations. Indeed, Kaupulehu Irr. 2 (4757-02) did not encounter ground water until the trachyte flow was penetrated. The first water was cold and had a chloride concentration of 94 mg/L (Stephen P. Bowles, personal communication, 2003).

Table 2. Trachyte elevation data as observed in Hualalai wells.

Well Name	Well No.	Trachyte Top Elev. (ft., msl)	Trachyte Bot. Elev. (ft.,msl)	Thickness (ft.)	Hydrology
Hualalai[1]	4258-03	292	190	102	high-level
Kalaoa[1]	4358-01	320	30	290	high-level
Kau 1[2] (Kohanaiki)	4458-01	481	341	140	basal
Kau 2[1] Kohanaiki)	4458-02	410	180	230	basal
Huehue 1[3]	4559-01	556	242	314	basal
Huehue 2[3]	4459-01	234	-36	270	basal
Huehue 3[3]	4558-01	729	149	580	basal
Huehue 4[3]	4459-02	1,148	990	158	basal
Huehue 5[3]	4558-02	768	32	736	high-level
Kaupulehu Irr. 2[3]	4757-02	5	-111	106	basal

[1]Geologic log compiled by CWRM.
[2]Geologic log compiled by Water Resource Associates.
[3]Geologic log compiled by Waimea Water Services.

The top of flow elevation data indicates that the trachyte lavas dip to the southwest. Kaupulehu Irr. 2 (4757-02) is somewhat anomalous in that the top of the flow is 5± ft., msl. The bottom of flow elevation can be influenced by pre-existing topography. The flow(s) is generally thicker in the vicinity of the Huehue wells (the exception is Huehue Ranch 4), which could be explained by the northwest rift zone being the possible vent for this eruption. Because trachyte lavas are much more viscous than basalt these lavas are much thicker and do not flow as far from the eruptive vent as basalt flows. Huehue Ranch 2 (4459-01) well, situated between Huehue Ranch 1 (4559-01) and Kau 1 (4458-01), has the top of the trachyte flow in a lower than the two adjacent wells (a structural graben?). The bottom of the flow at –36 ft., msl is significantly lower than the neighboring wells. The fact that trachyte occurs higher in the stratigraphic column at Huehue Ranch 4 (4459-01) could mean that this flow is from a younger lobe of trachyte that does occur at the adjacent wells.

The surface expression of Hualalai's northwest rift zone includes cinder, spatter cones, and fissures which occur north of Keahole Airport. The northwest rift was the source of Hualalai's last eruption in 1801. Recent geologic mapping and dating of the lava flows originating from the northwest rift determined that a majority of the exposed lavas are less than 5,000 years old (Moore and Clague, 1991). Volcanic dikes and other subsurface intrusions in the rift zone will affect water levels and the direction of ground-water flow. As noted, trachyte does not occur on the surface in the rift zone, but does outcrop on the surface at Puu Waawaa and Puu Anahulu. The age of this flow is determined to be 105,000 years (Langenheim and Clague, 1987). In a conversation with the author, Clague suggested that the trachyte flows found in the North Kona wells are younger than Puu Waawaa and Puu Anahulu because these flows are more "evolved" in terms of greater silica and alkali content (David Clague, personal communication, September 17, 1993). Recent dating shows the age of the trachyte flows range from 114,000 to 92,000 years ago. The oldest being the Puu Anahulu flow (Cousens and others, 2003).

The USGS' Geologic Branch, using side-scan sonar, has mapped several large and distinct submarine landslide and debris deposits west of the Kona Coast. Large blocks, some 1,500 ft. high, slid off the flanks of Mauna Loa (dredge samples collected from the debris are geochemically identical to subaerial Mauna Loa rocks) and are now resting on the seafloor west of Hualalai. Another feature, named the North Kona Slump, a Hualalai landslide older than 130,000 years, left a large escarpment over which younger subaerial lavas flowed (Moore and others, 1992; Moore and Clague, 1992).

As new wells are drilled throughout West Hawaii, drill cuttings should be described in detail and logged with care. Much of what is known about the subsurface geology of Hualalai can be attributed to the number of wells drilled through the 1990's. Many of the well cuttings are archived at the USGS Hawaii Volcano Observatory (HVO), providing an opportunity for further study, and to better understand the subsurface geology. Private well owners and developers have been very cooperative in providing data and preserving the drill cuttings at HVO.

4. Ground-Water Occurrence

As mentioned in the Introduction, ground water occurs not only as a thin basal lens, but also as high-level aquifers. The occurrence and behavior of the ground-water bodies is a reflection on the nature of the subsurface geological properties of the rocks, the internal structure of the volcanic edifice, as well as climate, seasonal rainfall patterns and concentration of rainfall.

4.1. Basal Ground Water

Basal ground-water occurs as a fresh water lens floating on denser underlying seawater, under Ghyben-Herzberg conditions. The Ghyben-Herzberg Principle states that every foot of fresh water above sea level is balanced by 40 feet below sea level. Tidal fluctuations and climatic changes to recharge cause a zone of mixing between the fresh water portion and the seawater below. This zone of mixing is known as the transition zone. Basal ground water occurs within permeable dike-free flank lava flows. Because of this relationship wells that are drilled too deep or are over pumped are susceptible to seawater intrusion. Since the island of Hawaii is young, there is no sedimentary coastal plain, or caprock, developed, as found on older islands (e.g. the Ewa Caprock, Oahu). This lack of low permeability terrestrial and marine sediments overlying the basal aquifer makes the outflow of fresh water and the intrusion seawater much easier. This causes basal water levels to be lower than found on older islands and the water more susceptible to higher salinity.

Basal water levels vary from 1.5± ft. to 12.5± ft. msl. It is assumed that most of the basal wells are unconfined (the water table is open to the atmosphere), although some water levels suggest semi-confined conditions. Wells 4458-01,02, 4558-01, and 4559-01 drilled in Kau (Kohanaiki) and Huehue Ranch (the HR wells) maybe semi-confined based on the greater than normal water levels. Water levels range from 7.5± ft., msl to 10± ft., msl with the hydraulic gradient to the north. Bowles (personal communication, 2003) noted that the Huehue Ranch wells 1-4 did not encounter ground-water at sea level, but artesian water rose after penetrating the first permeable lava flow below sea level.

Dikes associated with Hualalai's northwest rift and other subsurface structures could be responsible for the water level conditions encountered in this area. Figures 2a and 2b are water level maps of basal ground water in the Kailua-Kona to Kaupulehu region and from Puu Anahulu to Ouli region. Note that the higher water levels associated with the Ouli wells, and the direction of ground-water flow, is different from basal wells several miles south.

Geologic structure and lava flow permeability are the primary reasons for water level variability. Recharge of ground water into the aquifer systems by rainfall also causes water level variations. For example, given the same lava flow permeability, greater recharge will create higher water levels. Permeability of lava flows is expressed by the term "hydraulic conductivity" (**K**), in units of ft./day. Mathematically, it is the constant of proportionality between the specific discharge of ground water over a specific water level gradient of a given length (Freeze and Cherry, 1979). Aquifer tests conducted during the development of pumping wells can determine hydraulic conductivity values. Another method is to analyze the tidal responses in wells.

Typically, dike-free flank basaltic lava flows have hydraulic conductivity values greater than 1,000 ft./day, and where lavas are young and weathering is minimal, hydraulic conductivity is greater than determined on Oahu (Takasaki and Mink, 1982, Table 1). Oki (1999, p. 12) summarizes work that estimated hydraulic conductivities of flank flows in North and South Kona as ranging from 500 ft./day. to as high as 33,900 ft./day in some wells near the ocean that display a large water level variation in response to ocean tides.

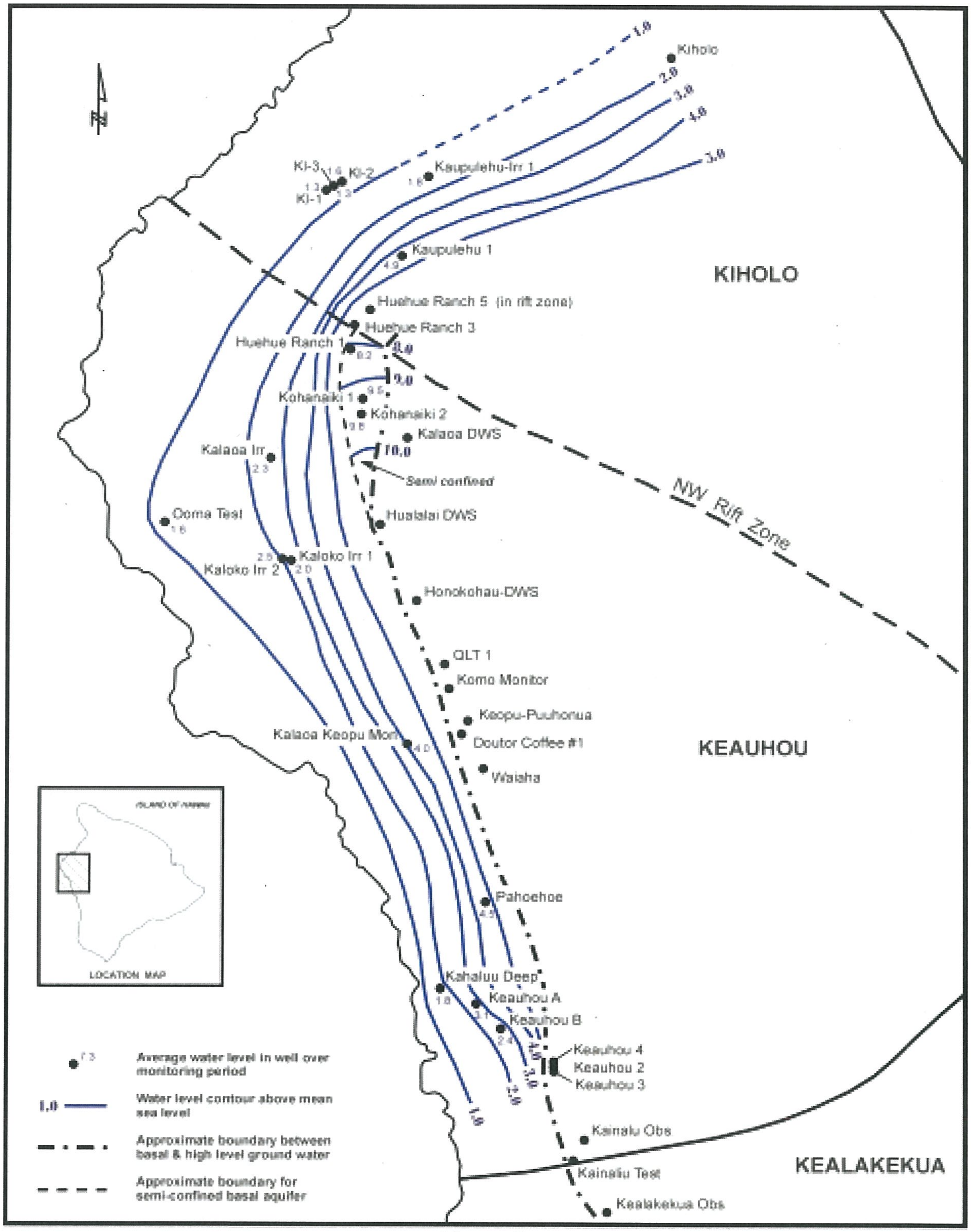

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Figure 2a

Figure 2a. Water level contours from Kiholo to Keahou.

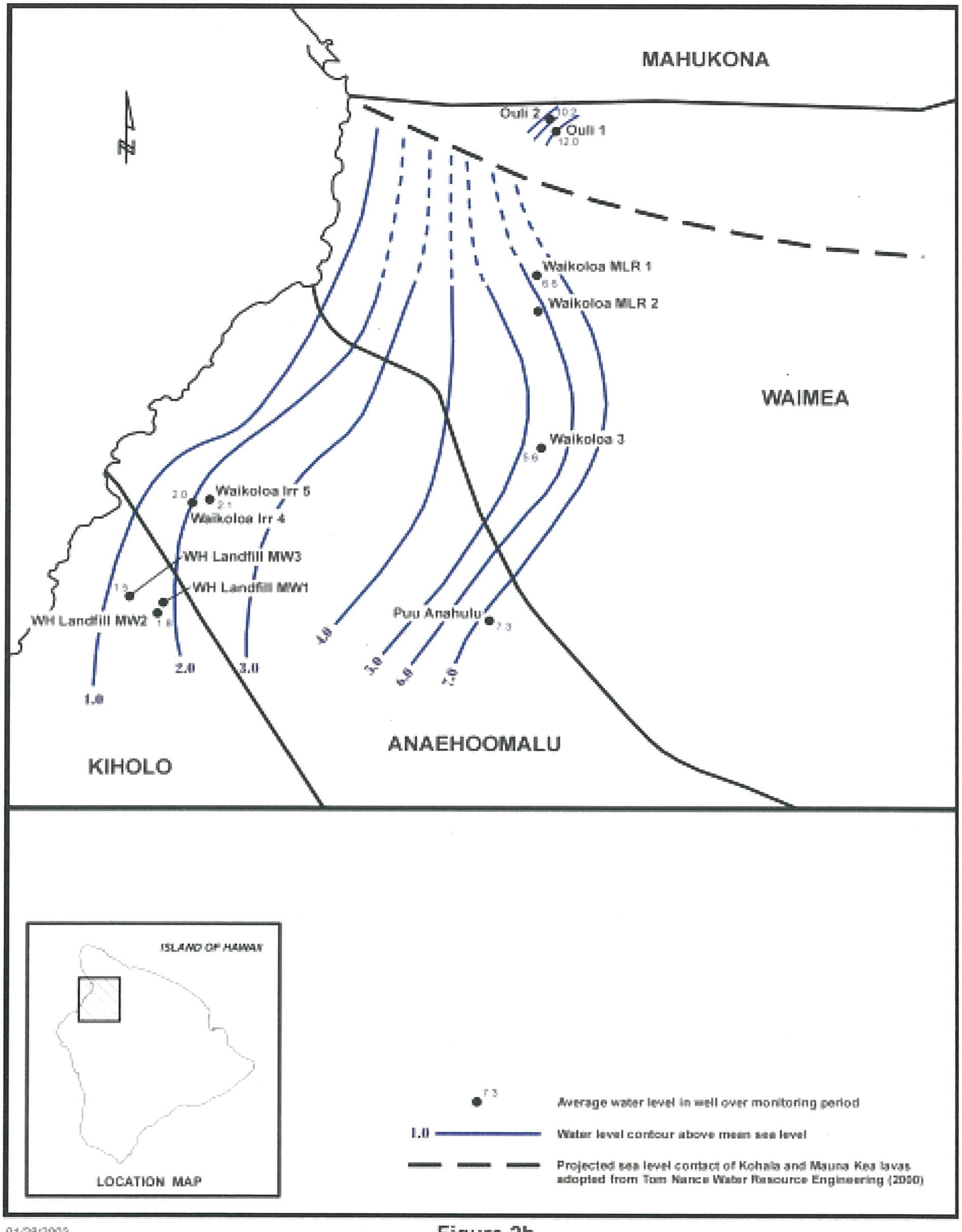

Figure 2b. Water level contours north of Kiholo.

During the development of the drinking water sources for the Kailua-Kona region, early exploratory wells were abandoned because of water levels less than 3 ft., msl and/or high chloride (greater than 300 mg/L) concentration. Later, new wells were drilled farther inland, where water levels are higher, and farther south near Keei (Kealakekua region), where recharge from rainfall is greater. In 1976, construction of the Kahaluu Shaft (3557-05) was completed. This is an inclined shaft starting at elevation of 590 ft., msl descending to a pump room near sea level connected to skimming tunnels with an invert elevation of –5 ft., msl. These tunnels skim the top of the basal lens and provide much of the drinking water to Kailua-Kona.

Similarly, resort development north of Kailua-Kona at Waikoloa and Mauna Lani also rely on basal ground water for drinking water sources and for golf course irrigation. These wells develop basal ground-water from aquifers within the flank lava flows of the Mauna Loa and Mauna Kea volcanoes. Chloride concentration from basal wells is a function of the distance the source is to the coast, the water table elevation, and the well's depth. Generally, chloride concentrations in basal sources are much more variable than in high-level sources.

Table 3 lists the basal wells that are in the network and their average water levels over the period of measurement (see Table 1). Also listed in Table 3 is the range (if available) of chloride concentrations recorded from these wells during the testing phase or later sampling.

As Table 3 shows, those wells where water levels are greater than 3 ft., msl usually exhibit potable water quality. Several exceptions are the Pahoehoe Well (3657-02) and Keauhou A (3457-02) where chlorides are greater than 200 mg/L. Keauhou A well, though unused, is near Kahaluu Shaft (3557-05) and may have been influenced by the high pumpage from the shaft. The water quality in the Pahoehoe Well is anomalous considering a water table elevation of 4.5 ft., msl and a bottom hole elevation of –34 ft., msl.

Table 3. Average basal water levels and chloride values (range) taken during testing.

Well Name	Well No.	Average Water Level (ft., msl)	Chloride Concentration (mg/L)
Keauhou B	3456-01	2.4	220-477
Keauhou A	3457-02	3.1	265-300
Kahaluu Deep Monitor	3457-04	1.8	N/A
Pahoehoe	3657-02	4.5	328-343
Keopu Deep Monitor	3858-01	4.0(27±)[1]	N/A
Kaloko Irr. 1	4160-01	2.0	950
Kaloko Irr. 2	4160-02	2.5	931-985
Ooma Test	4262-01	1.6	N/A
Kalaoa Irr.	4360-01	2.3	600-750
Kau 1 (Kohanaiki)	4458-01	9.5	33-37
Kau 2 (Kohanaiki)	4458-02	9.8	9-13
Huehue 1	4559-01	8.2	94
Huehue 3[2]	4558-01	(6.6) 4.8	90
Kaupulehu 1	4658-01	4.9	38-40
Kaupulehu Irr. 1	4757-01	1.8	250-275
Kukio Irr. 1	4759-01	1.3	1125
Kukio Irr. 2	4759-02	1.6	900
Kukio Irr. 3	4759-03	1.3	720-940
Kiholo	4953-01	2.0	340-352
Puu Anahulu	5347-01	7.3	60

Well Name	Well No.	Average Water Level (ft., msl)	Chloride Concentration (mg/L)
West Hawaii Landfill MW 1	5352	1.8	N/A
West Hawaii Landfill MW 2	5352	1.8	N/A
West Hawaii Landfill MW 3	5353	1.5	N/A
Waikoloa 3	5546-02	5.6	25-28
Waikoloa Irr. 4[3]	5552-01	2.0	472
Waikoloa Irr. 5[3]	5551-01	2.1	457
Waikoloa MLR 1	5846-01	6.6	50
Ouli 1	6046-01	12.0	52
Ouli 2[4]	6146-01	10.2	64

[1]Chase tube measurement and measurement in the well.
[2]Measured water level at time of testing 6.6± ft., msl. Airline water level average of 4.8 ft., msl.
[3]Sample reported in TNWRE, 2000, Table 5
[4]Thief sample during drilling.

On the other end of the scale, Kau 2 (4458-02) is extremely fresh at 10± mg/L chloride. The chloride concentration is anomalously low for basal water, and suggests that high-level ground water is spilling into this basal system from a nearby source. Kau 2 is 20± mg/L lower than at Kau 1, which is 2,000 ft. north and hydraulically down-gradient.

Table 4 examines ground-water gradients throughout West Hawaii between well pairs (i.e. mauka and makai wells) on a foot per foot (ft./ft.). basis and then normalized over one mile, and between inland wells and the ocean (assumed to be zero elevation) also on a ft./ft. basis and normalized over one mile. These gradients are similar or slightly less than gradients derived by Kanehiro and Peterson (1977) for the Kaupulehu and Waikoloa regions.

Table 4. Ground-water gradients.

Profile[1]	Well Pair (Up Gradient/Down Gradient)	Distance (ft.) (Δx)	Water Level Difference (ft.)[2] (Δh)	Gradient Δh/Δx (ft./ft)	Gradient (ft./mi.)
1	Keauhou A/Kahaluu Mon.	3,700	1.3	3.514E-4	1.855
1a	Keauhou A/Ocean	6,000	3.1	5.170E-4	2.728
2	Kaloko Irr. 2/Ooma Test	11,400	0.9	7.895E-5	0.417
2a	Kaloko Irr. 2/Ocean	15,400	2.5	1.623E-4	0.857[3]
3	Kau 2/Kau 1	1,400	0.3	2.143E-4	1.131
4	Kau 2/Huehue 1	6,400	1.3	2.031E-4	1.073
5	Kaupulehu 1/Kaupulehu Irr. 1	7,900	3.1	3.924E-4	2.072
5a	Kaupulehu 1/Ocean	21,400	4.9	2.290E-4	1.209
6	Puu Anahulu/Waikoloa Irr. 4	30,200	5.3	1.755E-4	0.927
7	Waikoloa Irr. 5/Waikoloa Irr. 4	800	0.1	1.250E-4	0.660
8	Ouli 1/Ouli 2	1,300	1.8	1.385E-3	7.311
8a	Ouli 1/Ocean	20,800	12.0	5.770E-4	3.046

[1]As shown on Figure 1

[2]Average water level data from Table 3.

[3]Oki and others (1999) report a ground-water gradient in the Kaloko area as 0.7 ft./mi.

Ground-water gradients provide insight about the direction of movement of ground water, aquifer properties, and subsurface geological structures (barriers). Ground-water moves from areas of recharge to the zone of discharge at the coast. Normal ground-water gradients range from less than one foot per mile to greater than 3 ft. per mile in South Kohala in the Lalamilo/Ouli area. Generally, steeper ground-water gradients either reflect higher rainfall and recharge or lower hydraulic conductivity. In the case of the Keauhou region of Hualalai, higher rainfall and steeply dipping lava flows probably create a steeper ground-water gradient (Profile 1 and 1a). The lowest gradient are north of Hualalai's northwest rift zone where lavas are thin-bedded and highly permeable. Recharge from rainfall is also less in this region as shown by Oki (1999, Figure 10). Low ground-water gradients are also found in Profiles 6 and 7, which are located in the Anaehoomalu Aquifer System (Northwest Mauna Loa Sector), an area where thin-bedded permeable basaltic lava flows and reduced recharge occurs.

The steep ground-water gradient between Ouli 1 and 2 wells, as seen in Profile 8, may be attributed to the lower hydraulic conductivity associated with denser and typically thicker hawaiite lavas (and possibly mugearite, if indeed, the bottom of these wells penetrates into Kohala lavas). Because of the arid conditions of South Kohala, the steep gradient reflected in Profile 8a may be the result of low hydraulic conductivity of the lavas rather than from direct recharge by rainfall. However, an influx of high-level ground-water from the Waimea-Kamuela region could be enough to increase the ground-water gradient.

4.2. High-Level Ground Water

Beginning in 1990, and continuing to the present time, the USGS, DLNR, Hawaii DWS, and private entities began exploratory drilling for potable sources at elevations greater than 1,600 ft., msl on Hualalai and Mauna Loa near Kealakekua. High-level ground-water elevations ranging from 25± ft., msl to 460± ft., msl were encountered. Where high-level ground-water occurs on other Hawaiian Islands, it is assumed that these high-level aquifers are not in contact with seawater (Ghyben-Herzberg conditions).

Normally, high-level ground water suggests that volcanic dikes associated with a rift zone or marginal rift zone are the cause. However, high-level ground water in North and South Kona does not appear to be associated with the mapped rift zones of Hualalai and Mauna Loa volcanoes. There are no surface features such as cinder cones or faulting to delineate a rift zone where most of the high water level wells are drilled (the only exception is Huehue Ranch 5, well no. 4558-02 drilled in Hualalai's northwest rift zone). On Hualalai the main rift zone trends northwesterly from the summit to the coast, north of Keahole Airport. Another rift zone trends southeast of the summit towards Mauna Loa, but its surface expression remains at high elevation.

Prior research provides several speculative interpretations about the subsurface conditions leading the formation of a high-level ground-water resource. Kinoshita and others (1963) produced a reconnaissance gravity map that suggested a buried north-south trending gravity anomaly paralleling the coast. Their gravity survey of Hualalai did not indicate the usual gravity anomaly associated with dense rock (dikes) at the summit. More recent detailed gravity work by Kauahikaua and others (1998, p. 14) indicate that the anomaly favors the "interpretation as dense lava flow, or a sequence of flows dipping westward rather than nearly-vertical dikes." They also point out that the western edge of the mass associated with this anomaly is "coincident with the hydrologic boundary." That would be the boundary between basal and high-level water. However, the possibility does exist that an ancient buried rift zone is present, and that water levels vary due to the size and hydrologic properties of the dike compartments. Work by Blackhawk Geosciences, Inc. (1991) for the State of Hawaii using time domain electromagnetic (TDEM) geophysical techniques near Palani Junction located a boundary trending about N50°W that delineates the high-level ground-water zone from the basal zone at a surface altitude of 1,400± ft., msl. The TDEM method cannot determine the cause of the boundary.

Summarizing the previous geophysical work, Oki (1999) presents three geological possibilities that could explain the presence of high-level ground water in West Hawaii. Figure 3 is adapted from Oki (1999). The first is the presence of vertical volcanic dikes that show a stepwise increase in water level farther inland from the coast (Figure 3a). The second possibility is normal faulting of Hualalai's flank with subsequent lava flows burying the faults, and presumably creating an impediment to flow as these flows draped over the fault scarps like a curtain (Figure 3b). The third possibility is dense westward dipping lava flows (as envisioned by Kauahikaua and others) trapping ground water between the dense flows (Figure 3c).

Figure 3b and 3c could also represent a situation where buried impermeable ash deposits (e.g. Pahala Ash, Stearns and Macdonald, 1946) create a para-basal condition as encountered on Guam (Mink, 1976). On Guam, an inclining impermeable basement formation elevates the ground-water levels to 40± ft. As the basement rock plunges well below sea level seaward of this para-basal aquifer, water levels drop to 10± ft., msl where Ghyben-Herzberg conditions to prevail.

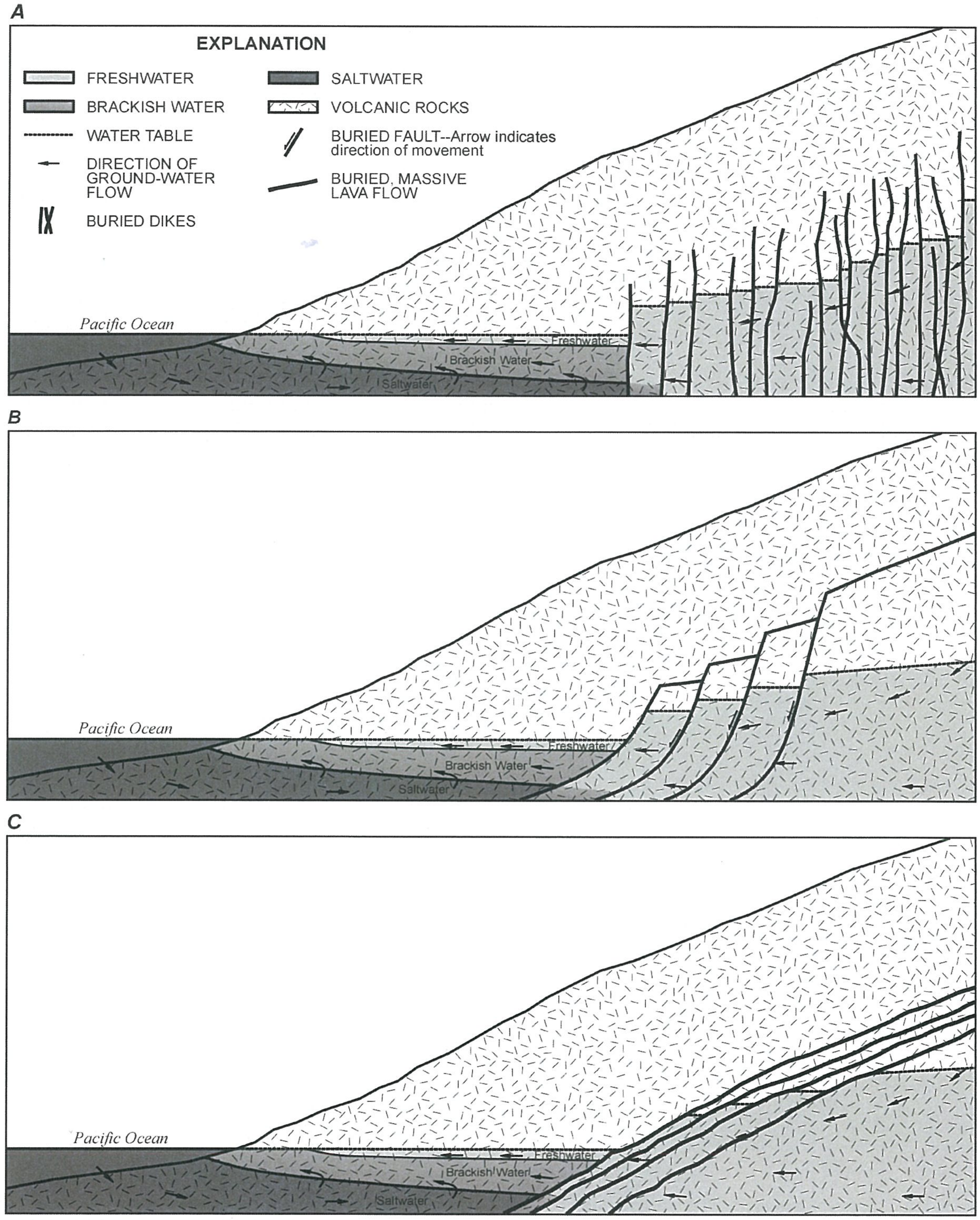

Figure 3. Three possible geologic structures that could impound high-level water.

Figure 3. Adapted from Oki (1999) Schematic cross sections showing geologic structures that may be impounding ground water to high levels (greater than 40 feet above sea level) in the Kona area, Island of Hawaii: (***A***) buried dike complex; (***B***) buried fault system; (***C***) buried, massive lava flows.

Indeed, ash layers were logged in the Keopu-Haseko well (3957-01) at depths of 960 ft. (715 ft., msl), 1040 ft. (635 ft., msl), and 1080 ft. (595 ft., msl) and were dated at 100,000 years (Clague, 1993, unpublished data). According to Clague (personal communication, September 17, 1993), the geochemistry of the ash encountered is distinctive indicating that the source was Mauna Kea. Weathered ash deposits lying on a fault scarp (Figure 3b) or layers of ash interbedded between lava flows, can create an inclining and impermeable basement or surface which could elevate ground water to the elevations encountered in the Keopu region. Ghyben-Herzberg lens conditions occur seaward of the Keopu-Haseko and Douter-Coffee 1 well (3957-04).

As stated earlier, most of the high-level wells are drilled above the 1,600± ft. msl elevation but below 2,000 ft. msl. Therefore, a relatively narrow band of wells exist from Kalaoa in the north to Kealakekua in the south. However, several exceptions exist. These are the Keei Well No. 4 (2753-03), drilled south of Kealakekua at an altitude of 1,347 ft. msl with a water level elevation of 357.7 ft. msl, Hokulia 1 (3155-03) at elevation 1,156± ft., msl with a water level of 51.2± ft., msl, and Huehue Ranch 5 (4558-02) at elevation 1,529 ft., msl with the water table at 24± ft., msl. No wells have been drilled south of Keei at sufficient elevation to determine the southern extent of the high-level ground-water body.

Analysis of accurate time-drawdown data collected from aquifer tests conducted at the DWS' Hualalai Well (4258-03) and Halekii Well (3155-02) provide hydraulic conductivity values (**K**) of 75 ft/d and 218 ft/d, respectively. Because the fresh water levels are several hundred feet above mean sea level in these wells and not under Ghyben-Herzberg conditions (where thickness of the aquifer can be calculated using the Ghyben-Herzberg Principle) the thickness of the aquifer is unknown. It is therefore assumed that the saturated portion of rock penetrated by the well is the thickness of the aquifer. In the case of Hualalai and Halekii wells, the thicknesses are taken as 432 ft. and 482 ft., respectively. The hydraulic conductivity values in the high-level ground-water wells are several orders of magnitude less than the basal wells. The aquifer test data also indicate that hydrologic boundaries were encountered. Abrupt downward changes in the measured drawdown suggest that dikes or dense lava flows form an impermeable boundary at some distance from the pumping well. There are some wells drilled into the high level aquifer that are good produce large quantities of water with little drawdown. An example is the State's Keopu Well (3957-05) that was pumped at 1,650 gpm with 13± ft. of drawdown.

As the high-level wells were drilled, a pattern of water levels emerged. Water levels are high in the north at Kalaoa (237.5 ft., msl), and steadily drop to the lowest water level in the Keopu area (40± ft., msl) above Kailua-Kona. From Keopu, the water levels rise progressively to over 450 ft., msl at Kealakekua. Figure 4 presents high-level water level contours for existing wells that illustrate this phenomenon.

Due to economic considerations, wells have not been drilled where the ground elevation is greater than 1,800 ft., msl. However, an exception is a well drilled at Kealakekua (Hokukano Ranch well 3153-01) at elevation 2,534± ft., msl and recorded a water level of 1,300± ft., msl. The bottom of well elevation is 1,180 ft., msl. During the pump test, the well produced over 400 gpm for over two days with little drawdown, indicating that this water body is extensive and probably not perched.

Even though the DWS' Kalaoa Well (4358-01) had a measured water level at 237.5± ft., msl in 1990, the bottom elevation is –57 ft., msl. When the DWS' Hualalai Well (4258-03) was drilled 1.5 miles south of Kalaoa Well, the initial water level was 191± ft., msl when the bottom elevation of the well was –43 ft., msl. After an initial aquifer test was performed, the well was deepened 99 ft. to –142 ft., msl. As a result, the water level in the well rose to 293± ft., msl. Deepening this well provides implications for ground-water flow in the high-level water body. The water level rise of 100 ft. suggests that the high-level aquifer is confined and that ground-water is under increasing artesian pressure the deeper a well is drilled. What happened to the DWS Hualalai well has implications for other high-level wells in the area.

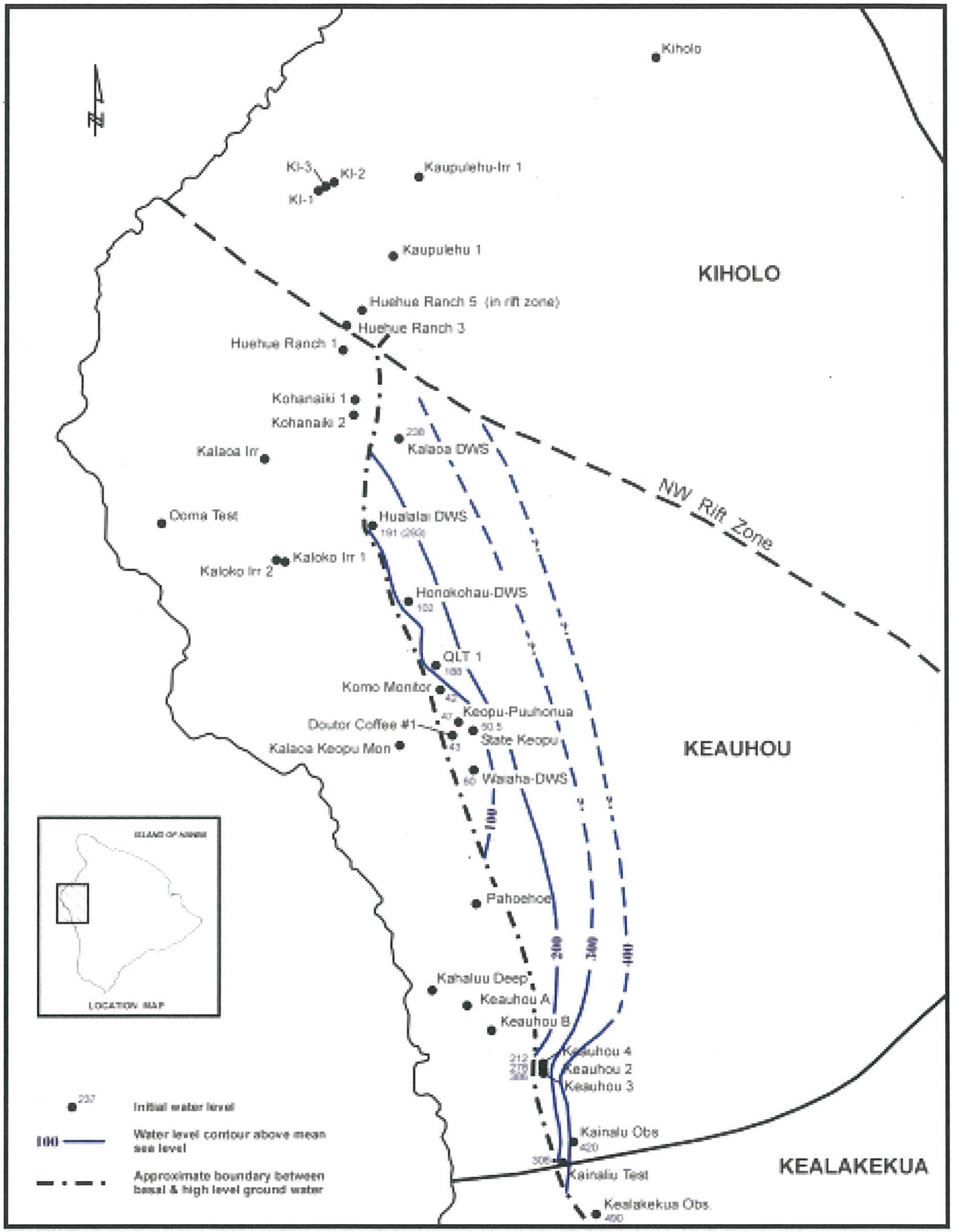

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Figure 4

Figure 4. Water level contours in the high-level aquifer.

Long-period records for water level measurements in these high-level wells are sporadic due to installation of pumps and other access problems. However, long-term water level measurements in the Hualalai Well (4258-03) and Keauhou-Kam 2 Well (3355-01) have shown a steady decline of water levels over time. Before the loss of access to Keauhou-Kam 3 Well (3355-02) and the DWS' Honokohau Well (4158-02), water levels demonstrated a similar decline over time. Periodic USGS measurements at their Kealakekua Observation Well (3155-01) also show that water levels dropped steadily over time. In addition, the Honokohau high-level well was showing a steady water level decline, but measurement ceased due to the installation of a new pump.

Table 5 presents data from the high-level wells including the initial water level and the last measured water level.

The straight-line rate of water level decline as shown in Table 5, provides a simple way to evaluate the size of the aquifer in the vicinity of the well. If one assumes that the impounded aquifers leak ground water at the same rate, and that specific yield (effective porosity) is equal throughout the water-bearing formations, then the slower the rate of decline, the larger the aquifer. This also assumes that pumping wells do not affect the measured water level (i.e. the pump is off and recovery is complete). To estimate an actual storage volume of an aquifer, better knowledge of the geometry and extent of the boundaries need to be determined.

Table 5. Water levels and water-level decline in high-level wells.

Well Name	Well No.	Year Drilled	Initial Water Level Date and Elevation (ft., msl)	Last Water Level Date and Elevation (ft., msl)	Total Decline (ft.) (No. of Days)	Rate of Decline Straight-Line (ft/d)
Keei No. 4	2753-03	1992	1992 (357.7)	N/A	N/A	
Kealakekua	3155-01	1991	9/6/91 (490.00)	8/17/01 (459.07[1])	30.93 (3633)	.0085[2]
Hokulia 1	3155-03	2002	10/21/02 (51.18)	N/A	N/A	
USGS Kainaliu	3255-01	1991	9/6/91 (420.13)	6/6/00 (406.66)	13.47 (3196)	.0042[3]
Kainaliu Test	3255-02	1993	8/4/93 (306.00)	N/A	N/A	
Keauhou-Kam 2	3355-01	1991	3/12/91 (278.09)	12/5/02 (269.51)	8.58 (4286)	.0020
Keauhou-Kam 3	3355-02	1992	1/29/93 (390.85)	9/9/97 (385.38)	5.47 (1684)	.0032
Keauhou-Kam 4	3355-03	1994	3/1/94 (211.46)	N/A	N/A	
Waiaha	3857-04	2000	4/9/01 (59.56)	N/A	N/A	
Keopu-Haseko	3957-01	1993	1/20/93 (47.20)	11/30/00 (45.06)	N/A	
USGS Komo	3957-02	1991	9/6/91 (42.20)	12/5/02 (42.36)	N/A	
Doutor-Coffee 1	3957-04	2001	5/2/01 (43.03)	N/A	N/A	
State Keopu	3957-05	2001	3/20/01 (50.62)	N/A	N/A	
QLT-1	4057-01	1994	11/15/93 (187.82)	N/A	N/A	
Honokohau-DWS	4158-02	1991	11/17/92 (102.50)	4/26/95 (98.19)	4.31 (890)	.0048
Hualalai-DWS	4258-03	1993	10/7/93 (292.44)	7/16/02 (275.38)	17.06 (3204)	.0053[2]
Kalaoa-DWS	4358-01	1990	1/14/91 (237.90)	N/A	N/A	
Huehue 5	4558-02	1992	9/25/92 (22.50)	12/3/02 (23.24)	N/A	

[1]USGS measurement (Taogoshi, and others, 2002)

[2]A pump was installed at the DWS Halekii Well, which is 50± from the USGS Obs. Well 3155-01. A pump was installed at DWS Hualalai Well 4258-03 in July 1998.

[3]Straight-line decline is based upon two measurements (see Appendix A).

However, to better evaluate the relative size (volume) of a high-level aquifer, all of the water level data should be used. The rate that water levels decline is exponential, not a straight-line. Mink (1962) developed an exponential decay equation in relation to the tunnel flows measured during the construction of Waihee Tunnel on Oahu. Hirashima (1971) and Takasaki and Mink (1985) used the exponential recession equation to relate tunnel discharge to aquifer storage:

$$Q = Q_o \exp(-bt)$$

where: Q = tunnel discharge at any time (days)

Q_o = initial discharge

b = recession constant

t = time (days)

Mink (1962), and later, Hirashima (1971), related aquifer storage or volume, V, as:

$$V = (Q_o - Q)/b$$

Using this relationship, Hirashima (1971) suggested that the recession constant, *b*, be used to determine the ease at which a tunnel can produce water or the ease for which recharge into the aquifer can occur over time. If *b* is large, then a tunnel can produce or recharge in a shorter period of time, than a smaller *b*.

The form of the equation that relate water levels is:

$$H = H_o \exp(-bt)$$

where: H = water level in the well at any time (days)

H_o = initial water level

b = recession constant

t = time (days)

Since we do not know what the rate of recharge or discharge, Q, is into or out of the aquifers, the relationship of aquifer volume can be related as a function of the change in the water level and the recession constant *b*. This can be written:

$$V = f\,((H_o - H)/b)$$

From this relationship, the aquifer volume, V, is inversely proportional to the recession constant, *b*. That is, the smaller the *b*, the larger the aquifer, and the longer it takes for the water levels to decline or to rise. The recession constants can also be used to compare relative volumes.

Table 6 presents the recession constant, *b*, for the high-level wells that have sufficient water level data (Appendix A). Computation of *b* was done using the computer program *TableCurve 2D*. Included in Table 6 is a comparison of relative volumes using the largest *b* value computed at DWS Honokohau as the baseline. Order of wells is by relative size. It is noted, however, that the recession constant for Honokohau-DWS is only based upon 11 measurements taken over a period of 890 days, and may not truly represents the decay constant for this aquifer.

Table 6. The exponential equation recession constant and relative volume comparison.

Well Name	Recession Constant, *b*	Correlation Coef. R^2	1/*b*	Relative Volume
Keauhou-Kam 2	7.047E-6	0.90	141,904	7.2
Keauhou-Kam 3	1.060E-5	0.89	94,340	4.8
USGS Kealakekua	1.575E-5	0.96	63,492	3.2
Hualalai-DWS	1.886E-5	0.97	53,033	2.7
Honokohau-DWS	5.106E-5	0.92	19,585	1

For some aquifers, the straight-line decline shown in Table 5 does not adequately describe the aquifer. For example, the USGS Kealakekua well shows that the straight-line equation slope (b) is 8.5E-3. This value is two orders of magnitude greater than the exponential recession constant shown in Table 6.

In summary, to better understand this high-level resource, it is imperative that monitoring water levels continue over time. In addition, aquifer testing of new high-level wells is performed as accurately as possible to ascertain hydrologic boundary information, and to more accurately determine aquifer geometry and volume.

5. Discussion of the Water Level and Chloride Data

5.1. Basal Ground Water

The basal water level data (see Appendix A) are presented by groups of wells located near enough to each other to be considered a regional cluster. Generally, basal water levels vary seasonally, and the magnitude of the variation is on the order of a foot. However, long-term water level changes lasting several years are observed and are probably related to climatic conditions. Quarterly instantaneous measurements, though coarse, do provide valuable long-term data on the resource and bracket the seasonal and climatic variability of water levels over the period of measurement. Water samples collected by CWRM personnel, while conducting water level measurements, were analyzed for chloride. Where appropriate, these data and other chloride data will be included with the discussion of the water levels.

Here, then, for future reference, are all the data collected for the West Hawaii wells. The data set for the basal wells consist of 636 separate measurements taken over 10 years.

5.1.1 Keauhou Region

Figure 5 shows water levels in basal wells in the vicinity of Keauhou and the Kahaluu Shaft. Basal ground-water levels in this area range between 1.5± ft. at the Kahaluu Deep Monitor Well (3457-04) to over 5± ft., msl at the Pahoehoe Well (3657-02). Water level data collection ceased at Pahoehoe and Keauhou B (3456-01) as access to these wells became extremely difficult. However, long-term measurements at Keauhou A (3457-02) show a rise in the general water level after January 2000. Kahaluu Shaft (3557-05), which pumps 5+ mgd and the Kahaluu Wells (3557-01-04) which pump about 2 mgd, may have some influence on water levels at Keauhou A and

Kahaluu Deep Monitor Well. Though the basal aquifer is unconfined, water levels in the vicinity of the shaft and wells have been lowered by combined withdrawal of 7± mgd.

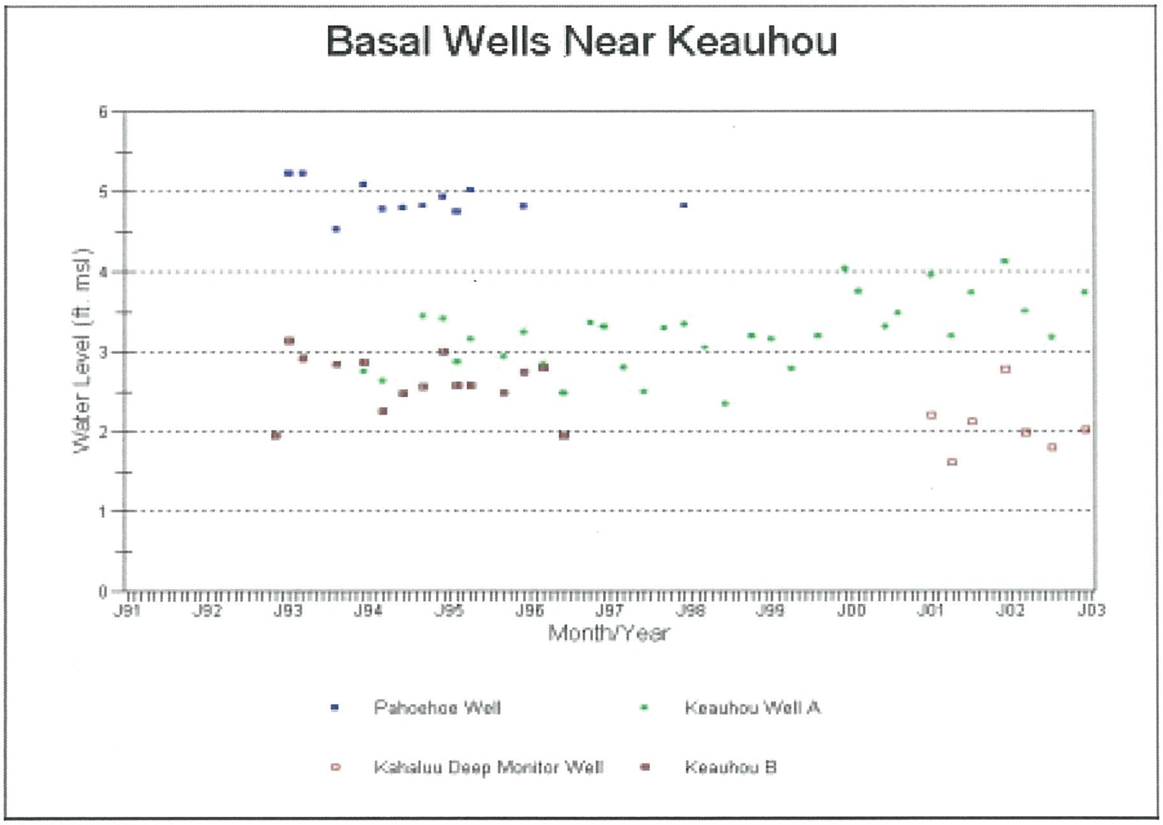

Figure 5. Basal wells in the Keauhou region.

Installation of a pressure transducer in Kahaluu Deep Monitor Well in November 2000 allows collection of daily average water levels. Figure 6 shows daily water changes for a two-year period. The daily water level graph indicates that the highest water levels are associated with the wettest months as depicted for the period of record at the Lanihau Rain Gage (Station No. 515330) above Kailua-Kona at elevation 1,530 ft., msl, and represented in Figure 7. Though the rainfall data are incomplete for 2002, there is a strong correlation between water levels and total monthly rainfall.

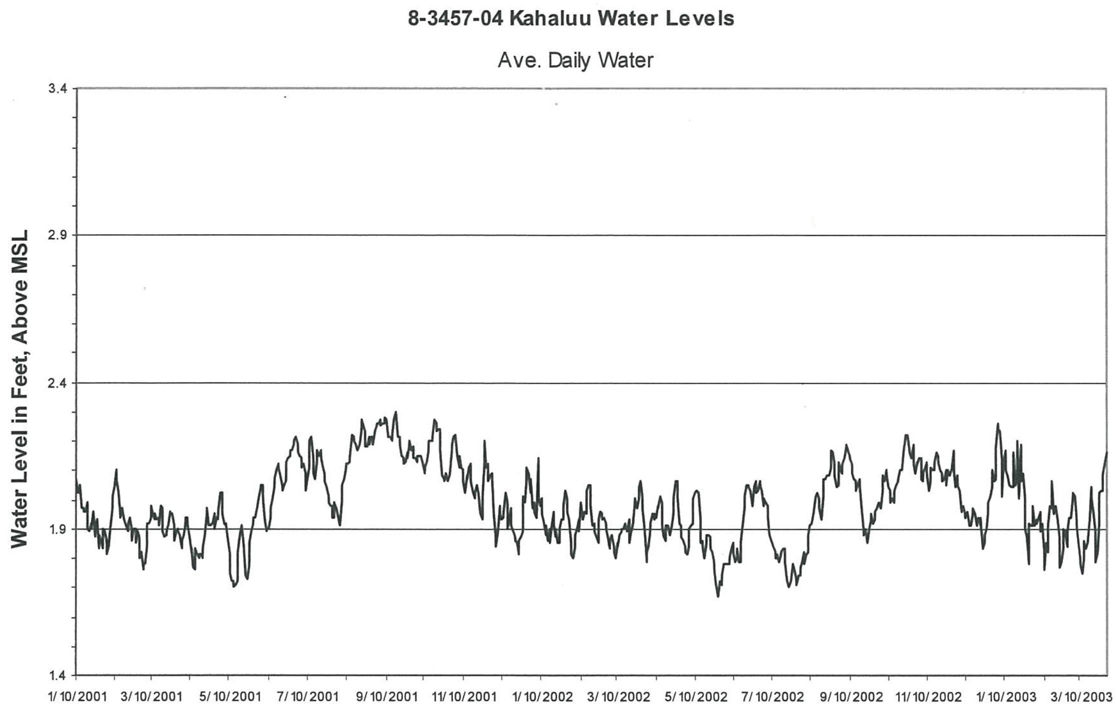

Figure 6. Daily average water levels at Kahaluu Deep Monitor Well.

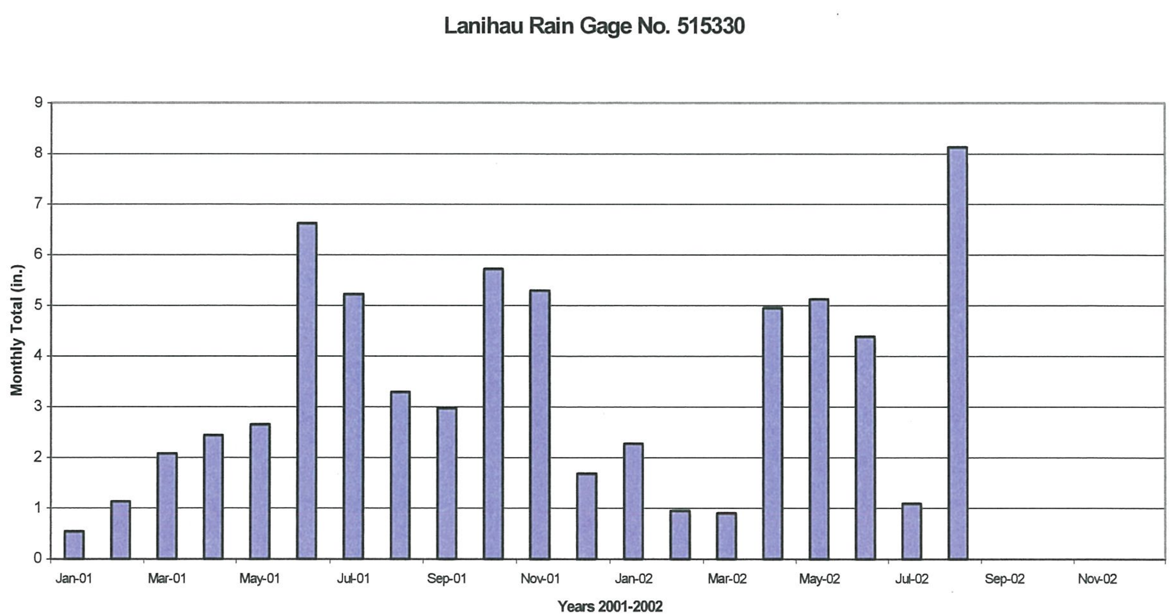

Figure 7. Monthly total rainfall for 2001-2002 at Lanihau Rain Gage 515330.

The Kahaluu Deep Monitor Well has been logged using a conductivity-temperature-depth sonde (CTD). The logging indicates that at the location of the monitor well, the conductivity (a measurement of salinity and expressed as micro Siemens per centimeter) at the top of the basal lens is greater than 1,000 µS/cm (≈250 mg/L chloride concentration or referred to as top of the transition zone). The mid-point of the transition zone of the aquifer (where the lens is half the chloride concentration of sea water or 9,500 mg/L or 25,000 µS/cm) elevation of the lens has remained steady at –47 ft., msl.

5.1.2 Kaloko-Kalaoa Region

Four basal wells were measured in this region since 1992. Two of them, Kaloko Irr. 1 and 2, had to be abandoned due to the sabotage of Kaloko Irr. 1 (4759-01) and to the loss of the access road to Kaloko Irr. 2 (4759-02).

The Kaloko-Kalaoa region is more arid than Keauhou, and as shown in Table 4, Profiles 2 and 2a are among the lowest ground-water gradients throughout the study area, which probably due to high hydraulic conductivity of the lavas and lower ground-water recharge. Both profiles are less than one foot per mile. Water levels in the region average about 2.5± ft., msl. Figure 8 presents all of the instaneous water level data collected.

The high hydraulic conductivity value for the lava flows in this area was demonstrated qualitatively when CWRM staff installed a pressure transducer in Kaloko Irr. 2 from December 7, 1994 to February 6, 1995. This 62-day period was sampled every 30 minutes. When the data was download and graphed, the response to ocean tides in the Kaloko well was remarkable. Figure 9 presents the tidal data for the Kaloko well. Kaloko Irr. 2 well is 12,400 ft. from the ocean. On January 1, 1995 the ocean tide amplitude between (one half of the tidal range) high and low tide was 1.1 ft. (tide chart). In the Kaloko well, the amplitude was 0.33 ft., a tidal efficiency of 30 percent, which indicates a highly permeable aquifer.

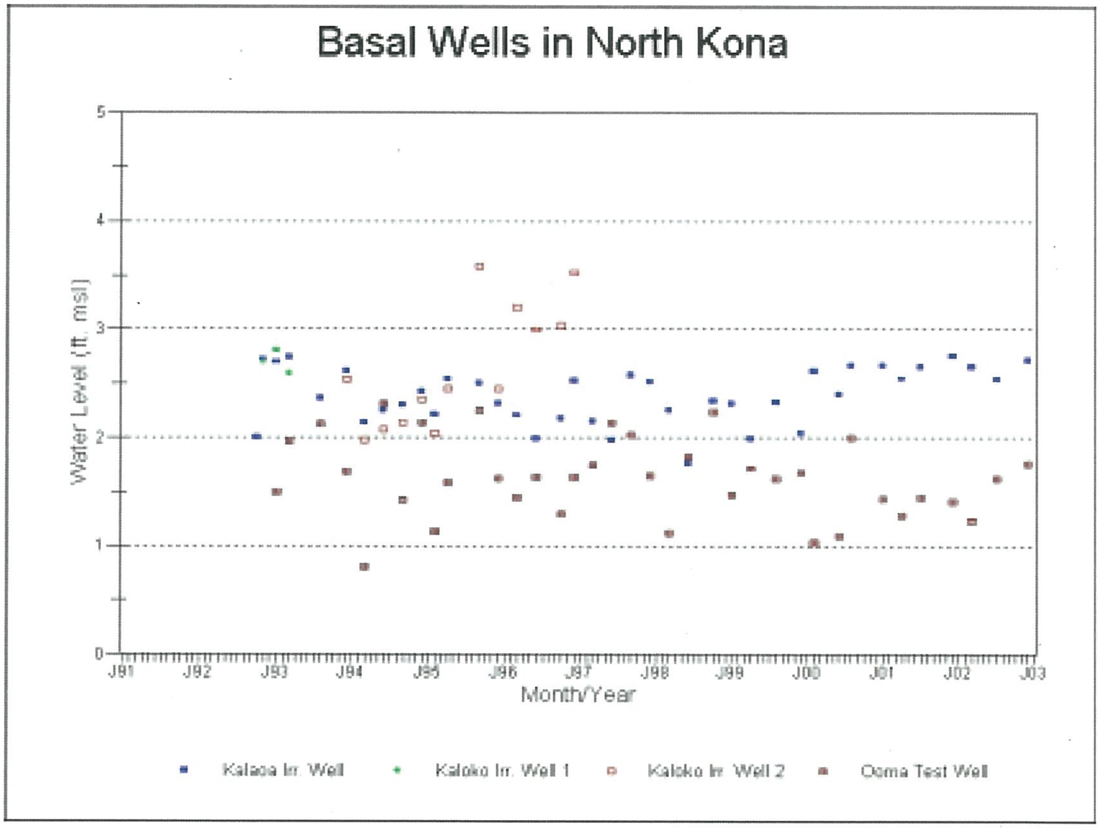

Figure 8. Basal water level data for the Kaloko-Kalaoa region

A quantitative estimation of the hydraulic conductivity in the Kaloko basal aquifer, which is in direct contact with the ocean, can be accomplished by relating the tidal response in the well to ocean. A simplified expression (Todd, 1980) is used:

$$h/h_o = \exp\left[-x\sqrt{\pi S/t_o T}\right]$$

Where: h = maximum amplitude of the tide in the aquifer, ft.

h_o = maximum amplitude of the tide in the ocean, ft.

x = distance the well is from ocean, ft.

S = storage coefficient or specific yield

T = transmissivity, ft^2/day

t_o = period of tidal cycle (about 0.5 days)

To solve for hydraulic conductivity, the equation has to be rewritten so that it takes the form:

$$\ln[h/h_o] = -x\sqrt{\pi S/t_o T}$$

$$\ln[h/h_o]^2 = x^2(\pi S/t_o T)$$

$$1/x^2(t_o/\pi)\{\ln[h/h_o]^2\} = S/T$$

If the maximum amplitude in the well (Figure 9) is 0.33 ft. (h) and the maximum amplitude in the ocean was 1.1 ft. (h_o) on January 1, 1995 (tide chart), and the distance (x) from ocean to Kaloko Irr. 2 is 12,400 ft., then assumptions must be made for the specific yield (S), and for the thickness of the aquifer, which in this case, extends below the fresh water lens. The thickness is unknown, but the saturated portion could extend several thousand feet below sea level.

To obtain the hydraulic conductivity value, the transmissivity must be divided by the thickness (T = Kz, where z is the thickness). Solving the equation for a specific yield of 0.1, and variable aquifer thicknesses, provide a range of values presented in Table 7:

Table 7. Estimated hydraulic conductivity from tidal data at Kaloko Irr. 2 well.

S/T	Transmissivity (T) ($ft.^2/day$)	Thickness (z) (ft.)	Hydraulic Conductivity K (ft./day)
2.5×10^{-9}	4.0×10^{7}	1000	40,111
		2000	20,055

The values presented in Table 7 are consistent with ocean tide analysis as reported by Oki (1999) in an earlier section of this report. However, the high hydraulic conductivity calculated by tidal analysis is fraught with uncertainties, and may be too high by an order of magnitude. Kanehiro and Peterson (1977) report tidal derived hydraulic conductivity values between 6,284 ft./day and 12,568 ft./day.

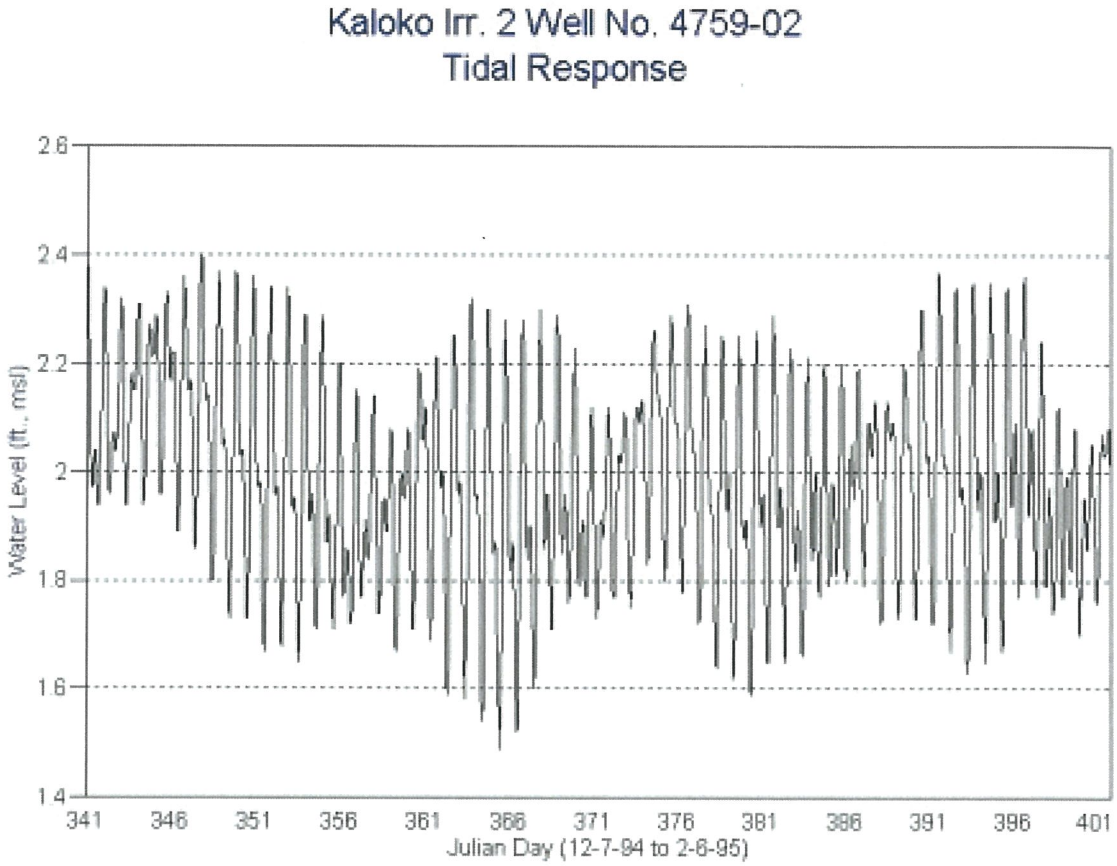

Figure 9. Tidal response in Kaloko Irr. 2 well no. 4759-02.

When the tidal signal is removed from the Figure 9 (using a USGS computer program), a smoothed water level in the well is obtained. These data show some tidal and barometric fluctuations on the order of 0.1 ft. However, by taking a 5-day moving average, a semblance of a “true” water level can be attained. Figure 10 illustrates a continuous water level for the 62-day period.

It appears that the low water level (Figure 10), which translates into a thin basal lens, is greatly influenced by ocean tides, suggesting that the brackish water lens is floating up and down on a long-term tidal signal.

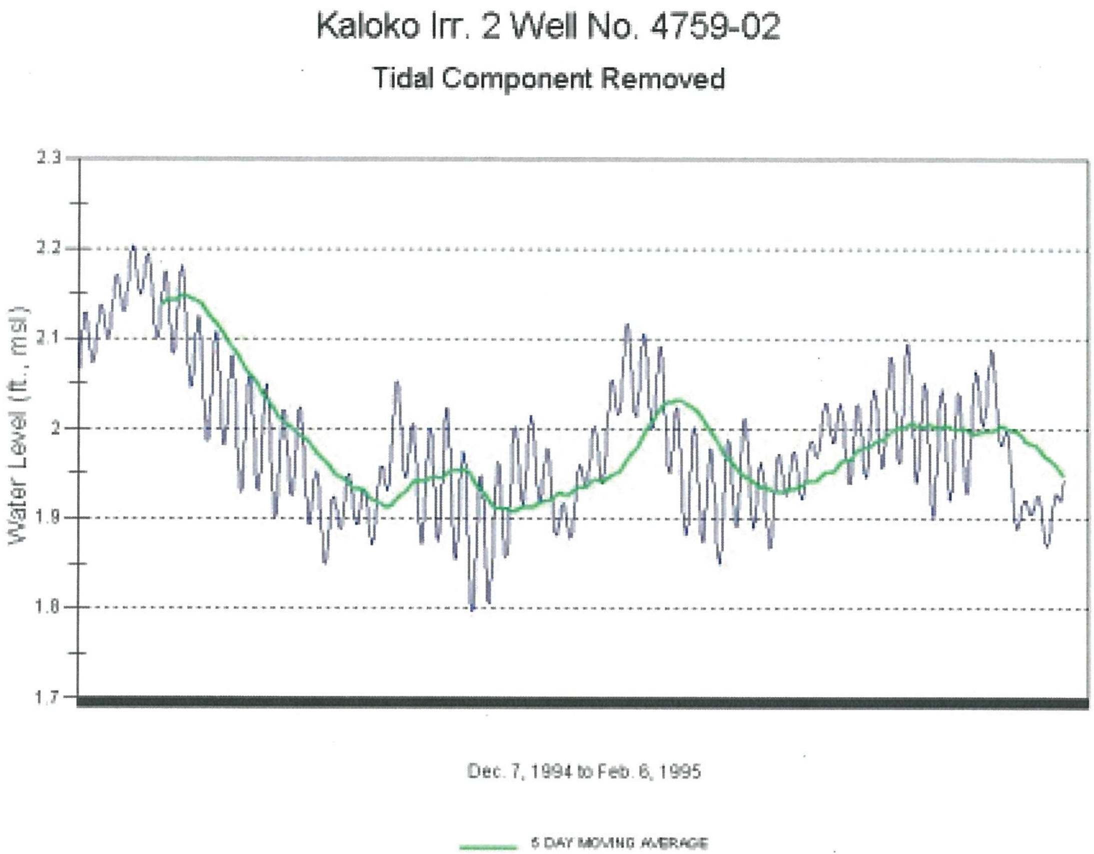

Figure 10. Tidal response removed and water levels smoothed.

5.1.3 Kau (Kohaniki)-Huehue Ranch Region

As mentioned above, the water levels found in the Kau and Huehue Ranch (HR) wells are much higher than would be anticipated by the ground-water gradient found in in the Kaloko-Kalaoa region at a lower elevation. The aquifer is delineated by the northwest rift zone (Huehue Ranch 5 well 4558-02), its northern boundary, and Kau 2 well to the south. A western boundary exists somewhere between Huehue Ranch Well 3 (4558-01) and the Kukio Irr. wells (4759-01-03) at an altitude of 600± ft., msl. It is assumed that the change from basal to the high-level water body begins at a ground elevation greater than 1,900 ft., msl. The aquifer is considered to be semi-confined.

Ground-water flow appears to be to the north, and the gradient between Kau 2

(4458-02) to other wells in the region is greater than 1-foot per mile. When Kalaoa-DWS well (4358-01) was drilled in 1990, and high-level ground water was encountered, private landowners began exploratory drilling at elevation of 1,800± ft., msl to locate additional high-level supplies. When Kau 1 did not encounter high-level water 1.3 miles to the north, Kau 2 was drilled closer to Kalaoa-DWS well but also found basal water. At the same time, the Huehue Ranch wells 1-4 (4459-01-02, 4559-01, 4558-01) were drilled to provide water for Makalei Golf Course and other developments in the area. Here again, basal water was encountered.

Water samples collected from the Huehue Ranch wells indicate that in some wells ground water may be affected by geothermal activity. According to Thomas (1986) and Cox and Thomas (1979), geothermal indicators in Hawaii's ground water are moderate-to-high silica concentration, above normal chloride/magnesium ratios. Used less extensively as an indicator in Hawaii are above normal sulfate/chloride ratios. Some of the indicators are found in the basal wells, but nothing that is definitive. For example, Huehue Ranch 2 (4459-01) has a silica concentration of 90.3 mg/L and a chloride content of 150 mg/L. Huehue Ranch 3 has chloride concentration of 14 mg/L and a sulfate concentration of 266 mg/L (Waimea Water Services and Akinaka and Associates, 1991).

Chloride concentration at the Huehue Ranch wells have varied from a low of 15 mg/L at Huehue Ranch 3 in the late 1990's to over 124 mg/L at Huehue Ranch 4 as reported in June 2001.

Figure 11 is a graph of water levels collected at Kau wells 1 and 2, and Huehue Ranch wells 1 and 3. The water levels in the Kau wells appear to hover about between 9.5 and 10.5 ft., msl. The water level at Huehue Ranch Well 1 averages 8± ft., msl until the end of 1998 when water level measurements show an increase to a high of 10 ft., msl in December 1999, and then settled to an average of 9 ft., msl.

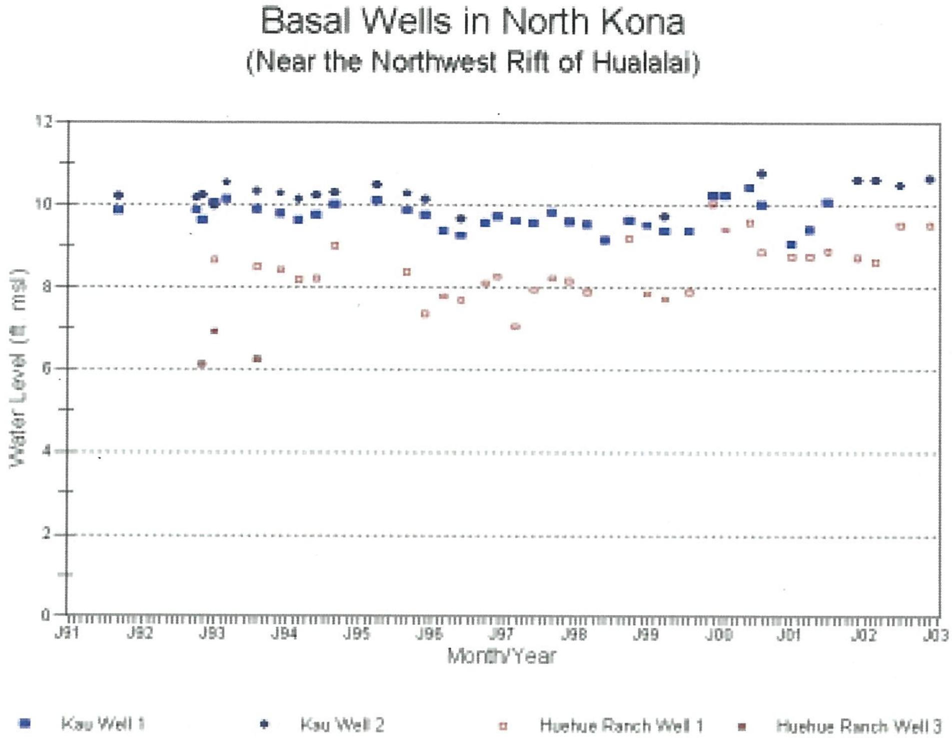

Figure 11. Water levels in the Kau (Kohanaiki)-Huehue Ranch region.

Least squares analysis correlating water levels between Kau 1 and Kau 2 (Figure 12), and between Kau 1 and Huehue Ranch 1 (Figure 13). The correlation coefficient (R^2) calculated in Figure 12 is reasonable at 0.61. Figure 12 also shows that there are several pairs that fall outside of the main trend line. If these pairs are removed from the least squares analysis, then the R^2 equals 0.89, and the new line equation becomes:

$$y = 0.937x + 1.0337$$

Where: y = the water level in Kau 2

Figure 13 shows the correlation between Kau 1 and Huehue Ranch 1, which is not as good as between the Kau wells.

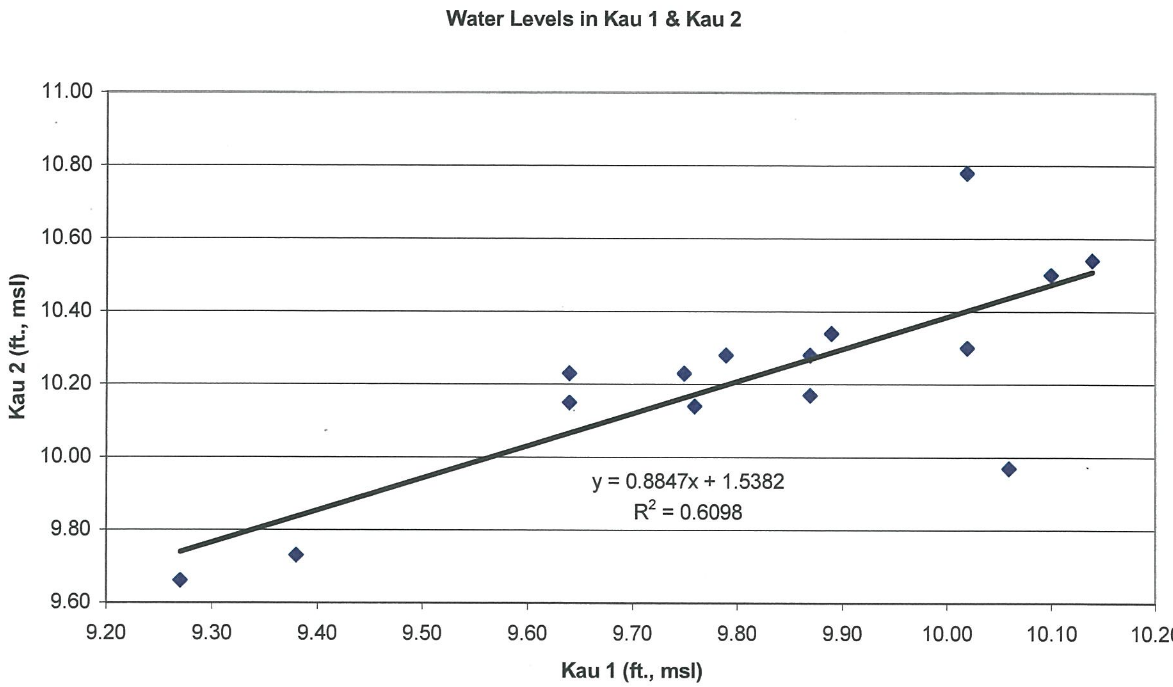

Figure 12. Correlation of water levels in the Kau wells.

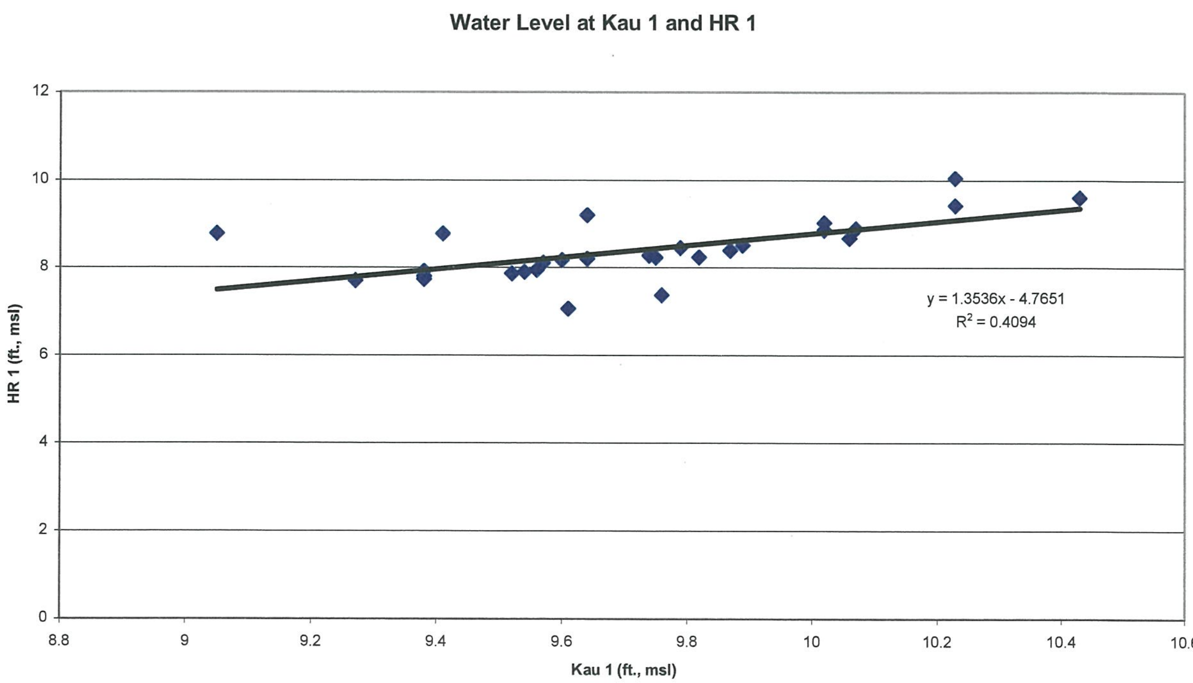

Figure 13. Correlation of water between Kau 1 and Huehue Ranch 1.

The R^2 for this correlation is 0.41. A possible reason why the correlation between Kau 1 and Huehue Ranch 1 is poorer than between the Kau wells could be due to the effects of pumping Huehue Ranch 2 (4459-01), which is situated midway between Kau 1 and Huehue Ranch 1.

With the installation of a new pump in Kau 2, it may be possible to observe changes in water levels in Kau 1 and Huehue Ranch 1. Aquifer drawdown during pump testing phase of these wells was low, nevertheless, a long-term change in water level may be observed directly and compared to the long-term measurements that CWRM staff has collected over the past 10 years. In addition, the correlation of water levels between non-pumping wells may become important as future development of the region occurs.

5.1.4 Kukio-Kaupulehu-Kiholo Region

Wells monitored in this region include both potable and non-potable sources. The non-potable sources are the Kukio Irr. Wells (4759-01-03), the Kaupulehu Irr. 1Well (4757-01), and the Kiholo Well (4953-01). Since water level monitoring began several new irrigation and potable wells have been drilled and will be incorporated into the network in the future.

The Kaupulehu Potable Wells 1 and 2 (4658-01, 02) are drilled 2,000 ft. northeast of Puu Nahaha, a vent structure on the northwest rift that erupted between 3,000 to 5,000 years ago (Moore and Clague, 1991). The wells are situated about 100 ft. apart. When these wells were pump tested in the 1980's chloride concentration ranged from the 36 mg/L to 42 mg/L. Kaupulehu Potable Well 1 was open and available for water level measurements until a pump was installed around March 1996. Since a temporary pump was installed in Kaupulehu Potable Well 2, CWRM staff routinely collected chloride samples when the pump was running. CWRM chloride data show that during the mid-1990's chlorides rose steadily from 51 mg/L on December 7, 1994 to 128 mg/L on October 13, 1998. Presently, the reported chlorides for these wells range from the high 100's to over 200 mg/L. Combined pumpage for the potable wells 1 and 2 is approximately 0.8 mgd. The wells' proximity to the northwest rift zone makes them candidates for pumping geothermally altered ground water. However, none of the geothermal indicators described above were observed.

The non-potable irrigation wells located between elevation of 600± (Kukio Irr. wells) and 900± (Kaupulehu Irr. wells) produce water with chlorides ranging from 900± to 1,600± mg/L at the Kukio battery and from 250± to 750± mg/L for the Kaupulehu Irr. wells.

The Kiholo well is located 6 miles northeast of Kaupulehu Potable Well 1, and was drilled in 1973 (State of Hawaii, 1973). The well was tested at 700 gpm and had a drawdown of less than one-foot. Chlorides during the testing phase varied between 330 and 352 mg/L, but remained steady at 345 mg/L.

Duarte (2002) measured salinity changes in the Kukio Irr. 1, 2, and 3 wells during pumping and after pumping ceased. He found that 75 percent of the rise in salinity took place during the first 12 hours of pumping during a week of testing. The salinity stabilized during this time period. After pumping ceased, salinity declined, but at a slower rate.

Duarte (2002) also investigated of whether upconing of saline water at the Kukio Irr. wells occurs below the well bore. He applied an analytical equation of Schmorak and Mercado (1969), and constraints to well depths and the interface with sea water as developed by Dagan and Bear (1968). He concluded from the salinity sampling that upconing did not occur. This conclusion suggests that both the vertical and horizontal hydraulic conductivities are high in this region.

Figure 14 presents water level data from the Kukio Irr. wells. Kukio Irr. 2 (4759-02) is on almost the same elevation contour with the other wells and the most northerly of the group, however, the data suggest that the ground-water gradient generally runs north to south. Unfortunately, access to measure Kukio Irr. 2 was blocked for over five years do to the installation of an emergency pump. New pumps were installed in the wells in 2000, which makes water level data collection more difficult due to new chase tubes and pumping schedules. CWRM was informed that one of the wells would have a monitoring system installed into one of the chase tubes (Stephen P. Bowles, personal communication, 2003).

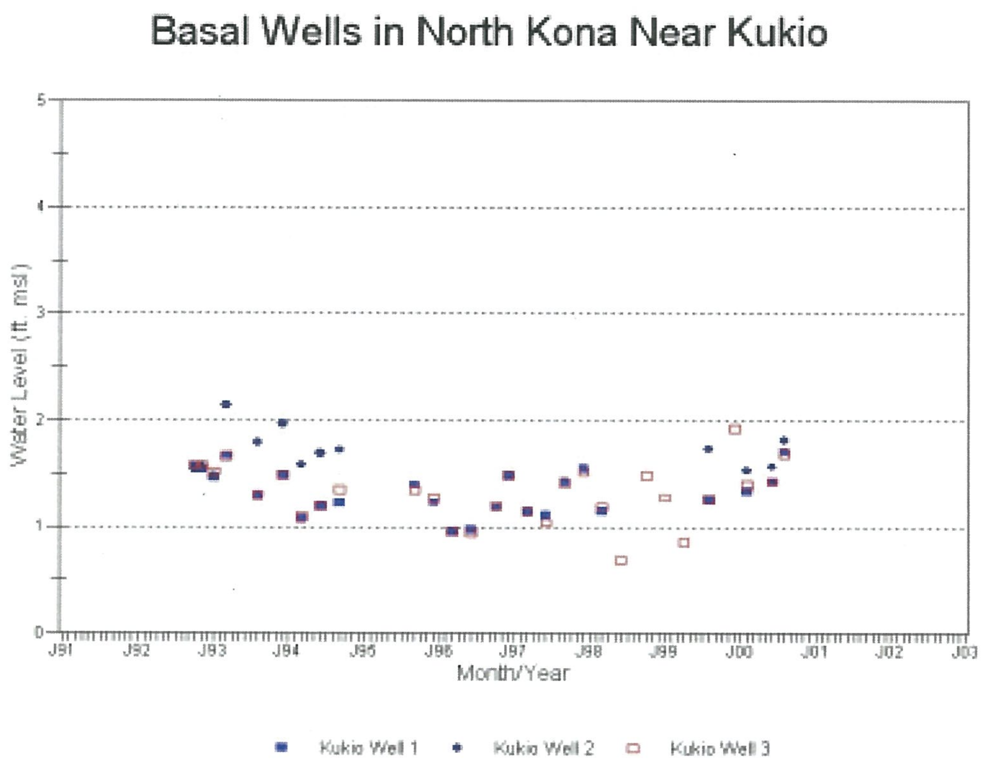

Figure 14. Water levels in the Kukio Irr. Wells.

The data also shows that during the mid 1990's water levels declined about 0.5 ft. and then began to rise again during latter part of 1999. Figure 15 plots the deviation of from the monthly median at the Huehue Ranch Rain Gage (State no. 92.1) from 1990 to 2002. Monthly rainfall records began in 1919, consequently the deviation from the monthly median indicates that the 12-year period of record depicted in Figure 15 is drier than normal. It is interesting that the rainfall for January 1997 is 19± inches above the median monthly (total rainfall was 21.45 inches for the month) did not show a corresponding response in water level elevation in these wells or wells depicted in Figure 11.

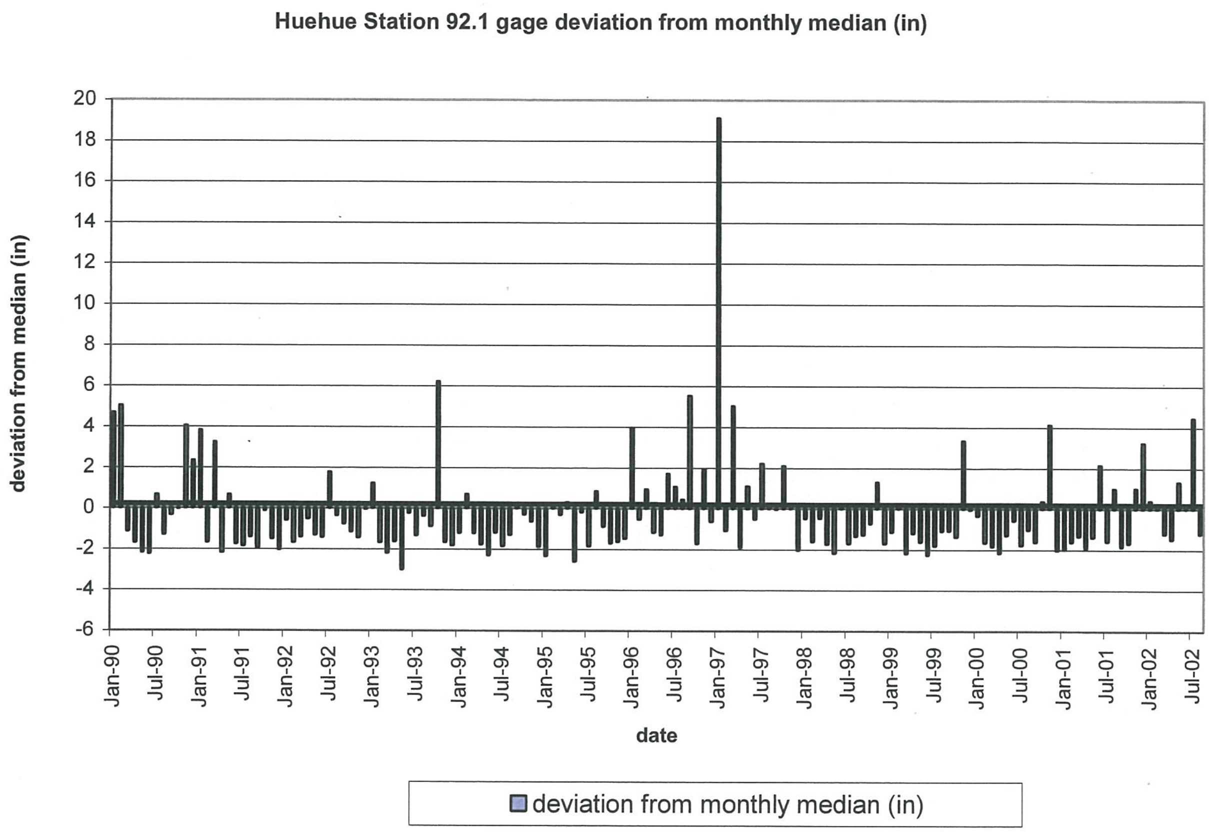

Figure 15. Departure of monthly median rainfall at the Huehue Station Gage 92.1.

Figure 16 presents water level data for Kaupulehu Pot. and Irr. wells nos. 4658-01, and 4757-01 wells respectively, and the Kiholo Well (4953-01). CWRM staff continued to collect water level measurements at the Kiholo Well until August 1999. At that time the USGS installed a recording pressure transducer, which allows for collecting average daily water levels. Figure 17 taken from the USGS "recent conditions" website (http://hi.water.usgs.gov/recent/4953-01.html), shows CWRM data and the continuous record data.

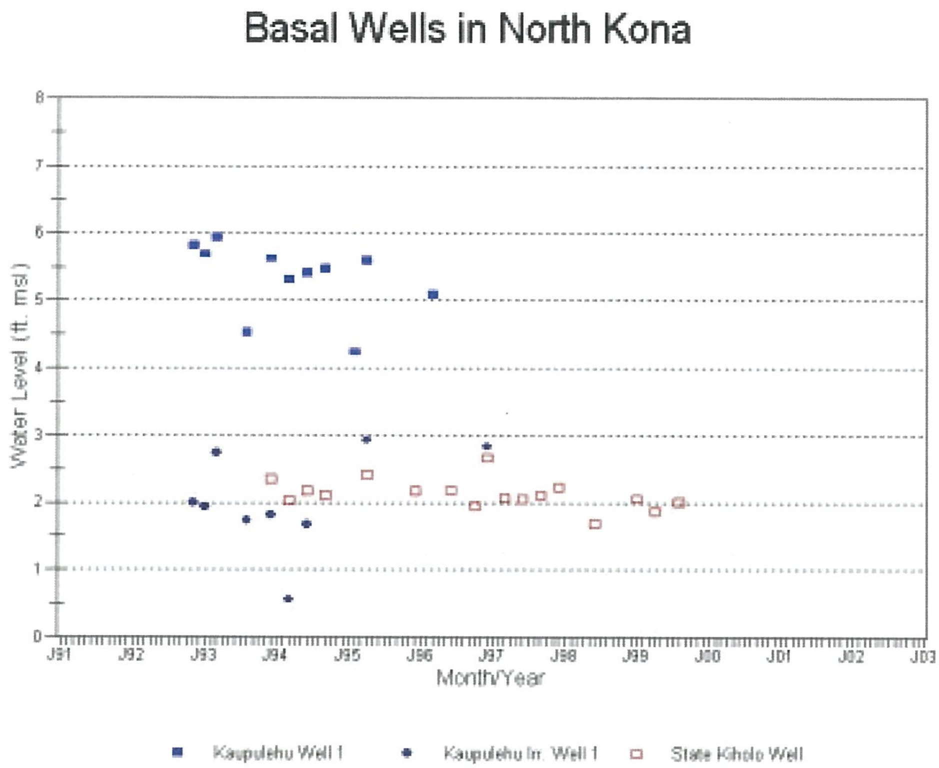

Figure 16. Water levels in the Kaupulehu and Kiholo wells.

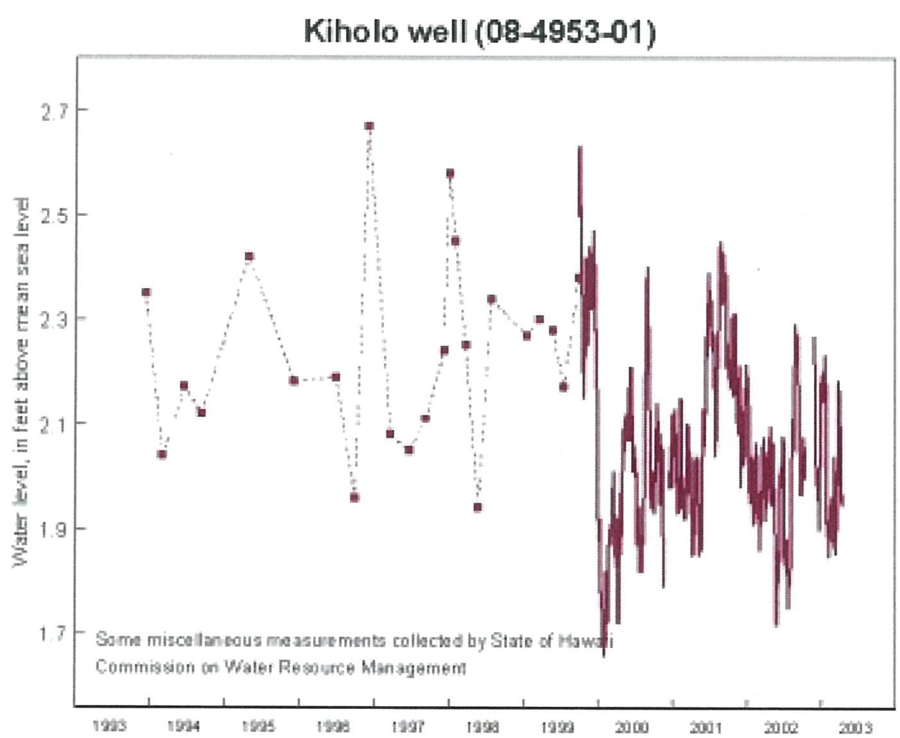

Figure 17. Water level at Kiholo well (from USGS).

5.1.5 Waikoloa-Puu Anahulu Region

Basal wells measured in this region include both potable and non-potable sources. Also included are three monitor wells located at the West Hawaii Landfill that sample for leachate in the ground water. The potable wells include Waikoloa 3 (5546-02) and the State's Puu Anahulu Well (5347-01). The non-potable wells are Waikoloa Irr. 4 (5552-01), Waikoloa Irr. 5 (5551-01), and the three landfill monitor wells. West Hawaii Landfill denotes them as MW 1, MW 2, and MW 3. MW 1 and 2 are located in the latitude/longitude block of 5352, while MW 3 is located in 5353. In addition, the landfill operates well no. 5352-01 as a source for wash water and dust control. Chloride concentration in this well is about 1,000 mg/L.

Waikoloa 3 was drilled in 1991 as a back-up source for Waikoloa 2 (5546-01), which supplies drinking water to Waikoloa Village. Initial chlorides were about 25 mg/L and the initial water level was 7.23 ft., msl. Water levels measured by CWRM were always less than the initial water level, which may be due to pumping Waikoloa 2 located about 1,200 ft. to the south. Water level data were collected from this well until a 1,000 gpm pump was installed in 1996. Current chloride concentration is 65± mg/L.

The State's Puu Anahulu well was drilled as an exploratory well in 1994 but was not cased and completed. However, the isolation of this well from existing wells makes it ideal as a ground-water monitoring site. The well was tested at 152 gpm and produced excellent quality water with chlorides of 60 mg/L. CWRM started measuring water levels in this well in December 1996 after loosing access to Waikoloa 3 in October 1996. Water levels are about 1.5 ft. greater than at Waikoloa 2, averaging about 7.5 ft., msl. Since December 1999, water levels have risen to over 8± ft., msl. Despite its isolation, the Puu Anahulu well was sabotaged sometime after March 2002. Steel pipes, connected by chains, were dropped into the well, though visual inspection suggests that the pipes are 20± ft. below the top of the surface casing and may be removed easily.

Waikoloa Irr. 4 and 5 wells were drilled though never developed. As shown in Table 3, chloride sampling has shown the concentration ranging from 450± to 470± mg/L. The basal lens is thin and any withdrawal of water by pumping will cause the chlorides to increase significantly. Waikoloa Irr. 5 is slightly up gradient from well 4, and as shown in Table 4, the ground-water gradient is 0.660 ft./mi. The average water level difference between the wells is 0.05 ft. The water levels in these wells range from 1.5 ft. to 2.5 ft., msl.

Figure 18 presents water level data for Waikoloa 3, Puu Anahulu, and the Waikoloa Irr. wells.

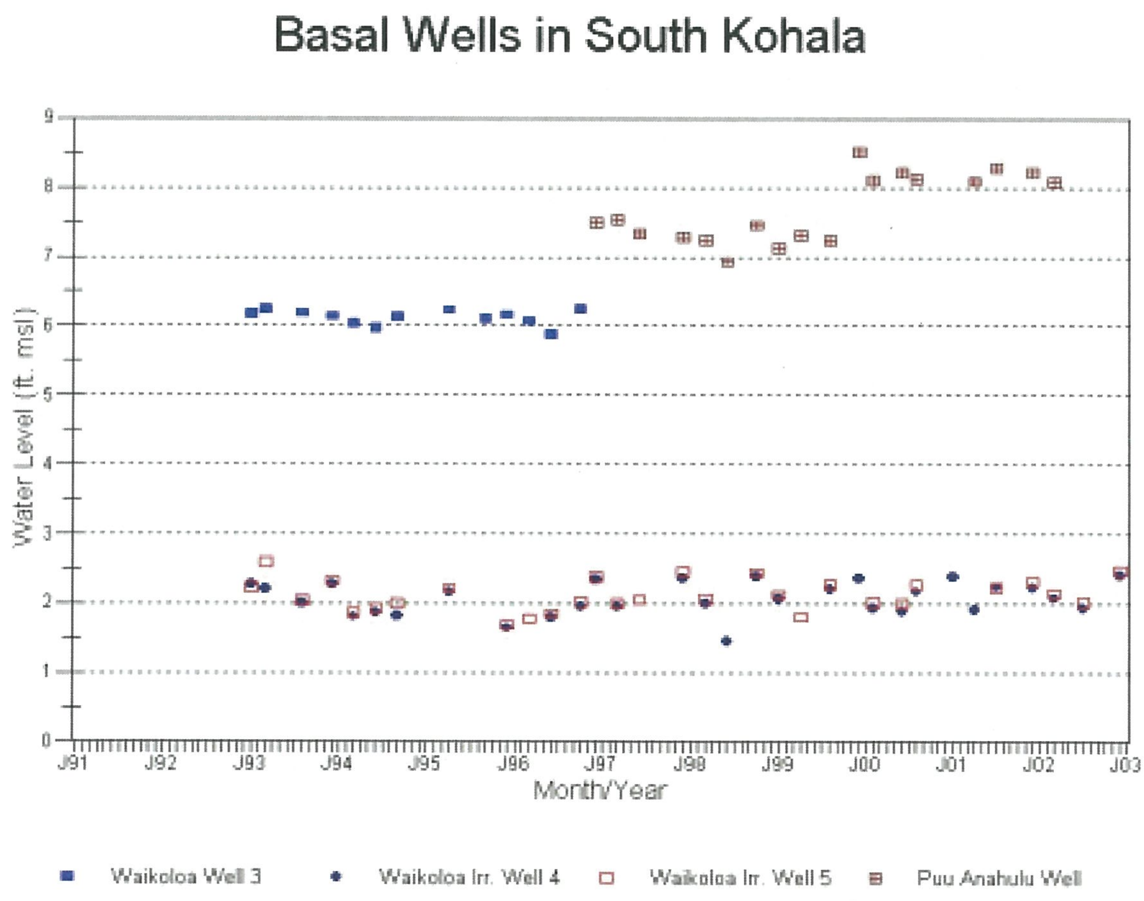

Figure 18. Basal water levels in potable and non-potable wells near Waikoloa, South Kohala.

The West Hawaii Landfill monitor wells (MW 1-3) provide a unique opportunity to measure the direction of ground-water flow. By measuring the water level in three wells within a 20-minute time span, the direction of flow can be calculated using the "three point method" (Compton, 1985). That is, the elevation of the water table is considered a planar surface, whose "strike" direction is the intersection of this surface with a horizontal plane. The azimuth direction of this intersection is then calculated by the three point method. Perpendicular to the strike, and down-gradient (towards the ocean), is the direction of ground-water flow.

Figure 19 uses the water level data collected at the MW wells from June 1996 to April 2003 and presents the average ground-water flow direction to be N80°W (azimuth direction of 281°). As seen in Figure 19, the range of ground-water flow direction varied from S48°W (228°) to N38°W (322°). Variability of the flow direction is related to the response of the basal lens to ocean tides. As shown above, ocean tides greatly influence water levels in wells many thousands of feet inland from the coast, and tidal efficiencies in these wells are quite high.

In addition to flow direction, an estimated average velocity of ground water can be derived from the water level data collected from the MW wells. The average velocity is calculated using the following equation:

$$V_{ave} = (Kdh/dl)/\theta$$

Where: K = hydraulic conductivity = assumed to be 5,000 ft./d

dh/dl = average ground-water gradient (ft./ft.) = 0.00011 (0.35 ft./3,300± ft. i.e. the distance between MW 1 & 3)

θ = effective porosity = assumed to be 0.20

Using the above equation, the average ground-water velocity within the landfill is 2.7 ft./day or 995 ft./yr. However, if the hydraulic conductivity is doubled, then the average velocity also doubles. The effective porosity of 0.20 (20%) is reasonable for recent aa lava flows.

Figure 20 presents all of the MW well data in graphical form. Average water level differences between the wells range from 0.35 ft. for the MW 1 (north well) and MW 3 (west well), to 0.03 ft. between MW 1 and MW 2 (south well).

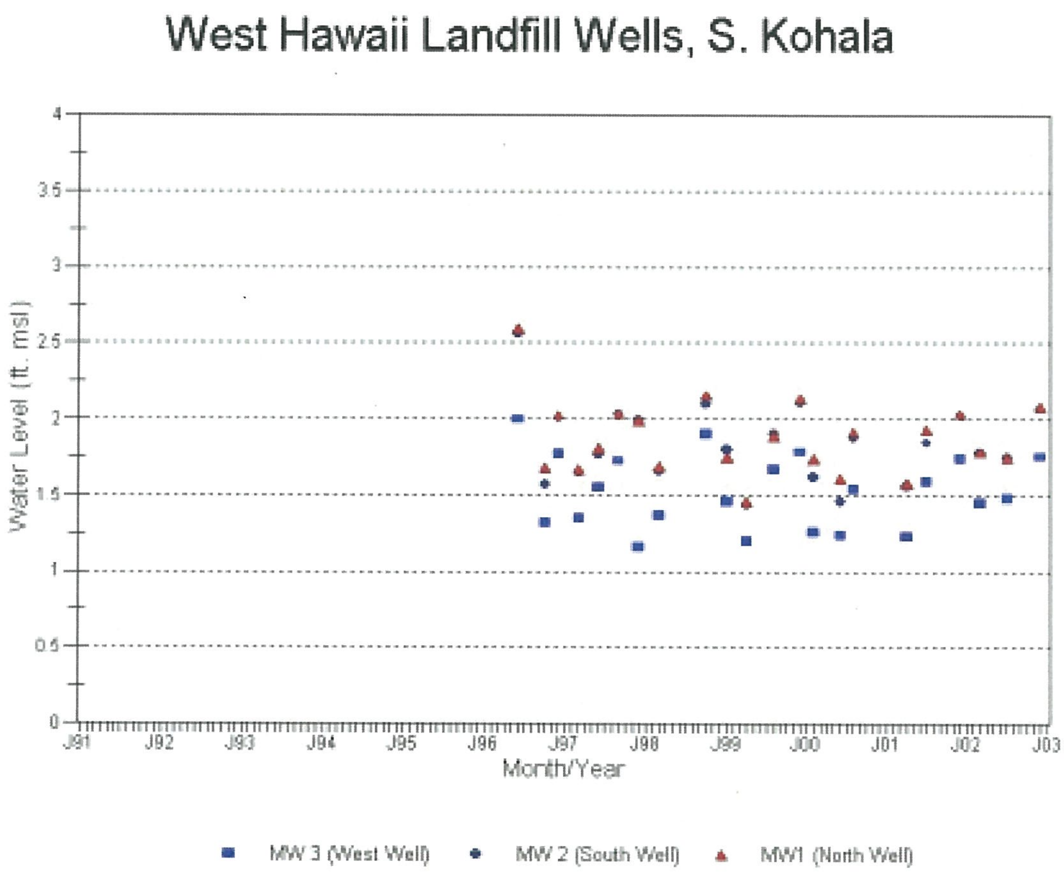

Figure 20. Water levels at the West Hawaii Landfill monitor wells.

5.1.6 Lalamilo-Ouli Region

North of Waikoloa Village are potable wells 5745-01-03 (Parker 4, 5, and DW-1) which are not in the CWRM ground-water network, but display anomalous water levels of 17± ft., msl and representative chlorides of 25 mg/L (TNWRE, 2000). These elevated water levels could be either due to a lower hydraulic conductivity or an increase in subsurface ground-water flux spilling over from the Waimea high-level water body. North of these wells are the DWS Lalamilo sources with water levels varying between 7 and 8.2 ft., msl, and representative chlorides between 40 and 90 mg/L (TNWRE, 2000).

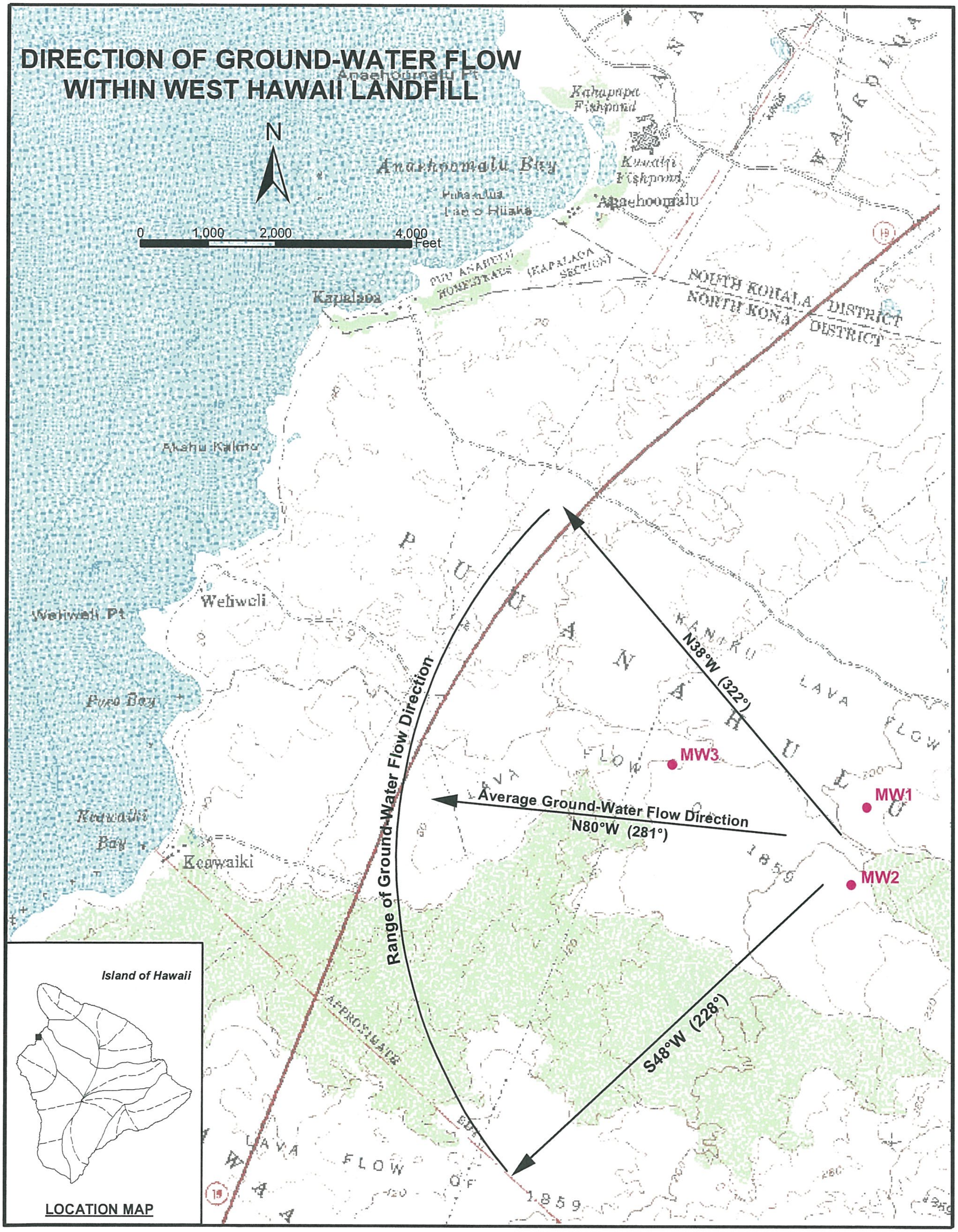

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Figure 19. Direction of ground-water flow at West Hawaii Landfill.

Wells 5846-01, 02, approximately a mile south of Lalamilo well field, were included in the network when drilled for Mauna Lani Resort (in this report referred to Waikoloa MLR 1). Hawaii DWS is now the owner/operator. CWRM measured the water level in well 5846-01 from 1993 until 1997, but only obtained one water level of questionable value (due to the lack of an adequate reference benchmark) in 1993 from 5846-02. These wells were put into service in 2000 and 1999, respectively. Well 5846-01 produces an average of 60 mg/L chloride water, while well 5846-02, which is closer to the 5745-01-03 well field (the Parker wells operated by West Hawaii Utilities), yields chloride values of 32 mg/L (TNWRE, 2000).

Ouli wells 1 and 2 (6046-01 and 6146-02, respectively) were drilled in the late 1980's for Signal Oil Company, but are now owned by Hale Wailani Partners. Ouli 1 was completed in 1989, but Ouli 2 has not been completed, a pilot hole was drilled but it has not been reamed out and cased. Only Ouli 1 was pump tested. The test revealed a drawdown of 5.2 ft. at a maximum pumping rate of 1050 gpm (1.5 mgd). Samples collected during the test were not analyzed for chlorides, but specific conductance measurements were recorded. Converting the specific conductance values, the estimated chloride is 50 mg/L (Mink and Yuen, 1989).

As shown in Table 4, the ground-water gradient between Ouli 1 and 2 is the steepest measured, with a normalized gradient of 7.311 ft./mi. A decline of an average of 1.8 ft. over 1,300 ft. of separating the wells is significant because the measured benchmarks are referenced to each other, being surveyed by the State surveyor in 1993. The cause for the drop in water level between the wells is unknown, though the suggestion that Ouli 2 well penetrates into the Kohala lavas could be the reason (TNWRE, 2000). A well drilled into the Kohala lavas (Mahukona Aquifer System), known as the Ouli Kawamata well (6145-01) is situated adjacent to the Kawaihae Road at an elevation of 1,572 ft., msl. CWRM staff measured water levels in this well twice:

11/29/94	12.60 ft., msl
12/7/99	11.13 ft., msl*

*Measuring point altered since the 1994 measurement. If a correction is made using the original measuring point elevation, then the water level is 11.60 ft., msl.

On December 7, 1999, the measured water level in Ouli 2 was 11.39 ft., msl. Ouli 2 is approximately 4,000 ft. southwest (down gradient) of the Kawamata well. If Ouli 2 is penetrating into Kohala basalts, then the adjusted measurement of 11.60 ft., msl is possible because of the Kawamata well is up-gradient. If the true Kawamata water level is 11.13 ft., msl, then the ground-water conditions encountered by Ouli 2 may be more related to those encountered by Ouli 1. The latter may be truer because the correlation of measured water levels in each of these wells is quite good; therefore, a least squares analysis correlating water levels between Ouli 1 and Ouli 2 is illustrated in Figure 21. If the two "outlier" points shown in the graph are disregarded, then the correlation coefficient, R^2, is equal to 0.93. The resulting new equation for the best-fit line becomes:

$$y = 0.9415x - 1.0706$$

where: y = the water level in Ouli 2

However, Bowles (personal communication, 2003) while measuring Ouli 2 with a water level data logger, encountered surface water entering the uncased well bore, suggested that the influx of this water may not provide a true water level in that well.

Figure 22 presents the water level data for the Ouli wells and Waikoloa MLR 1 wells in graphical format. Cursory examination of Figure 22 shows that, in general, water level elevations are slowly rising in the Ouli wells since late 1999, and may be attributed to climatic changes.

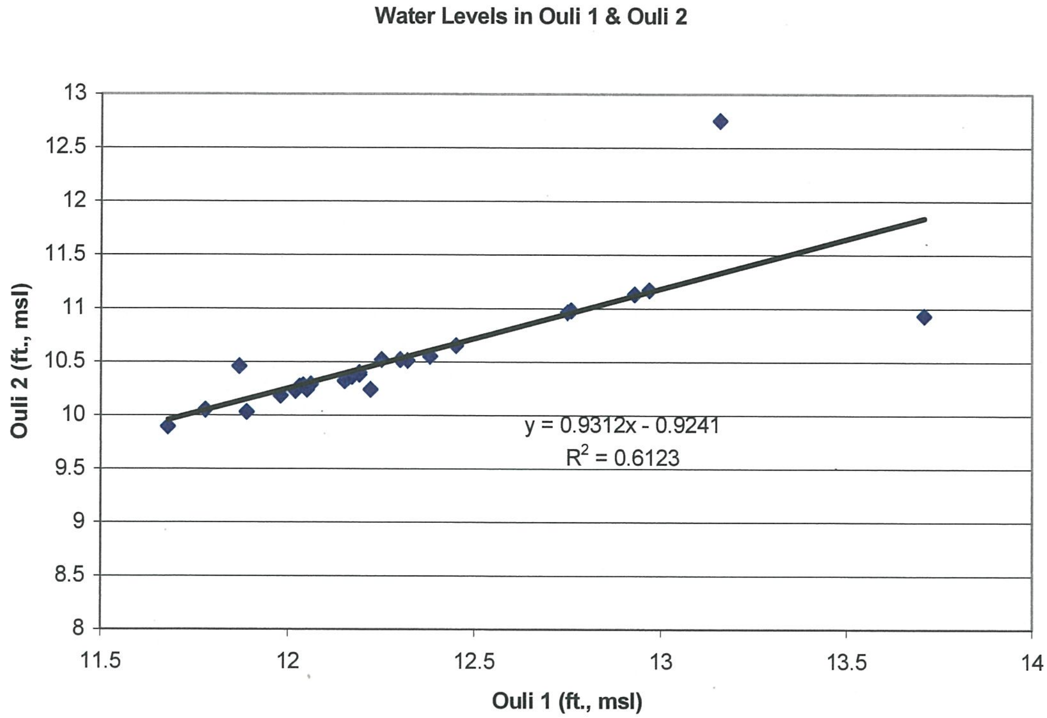

Figure 21. Correlation of water level in Ouli 1 and Ouli 2.

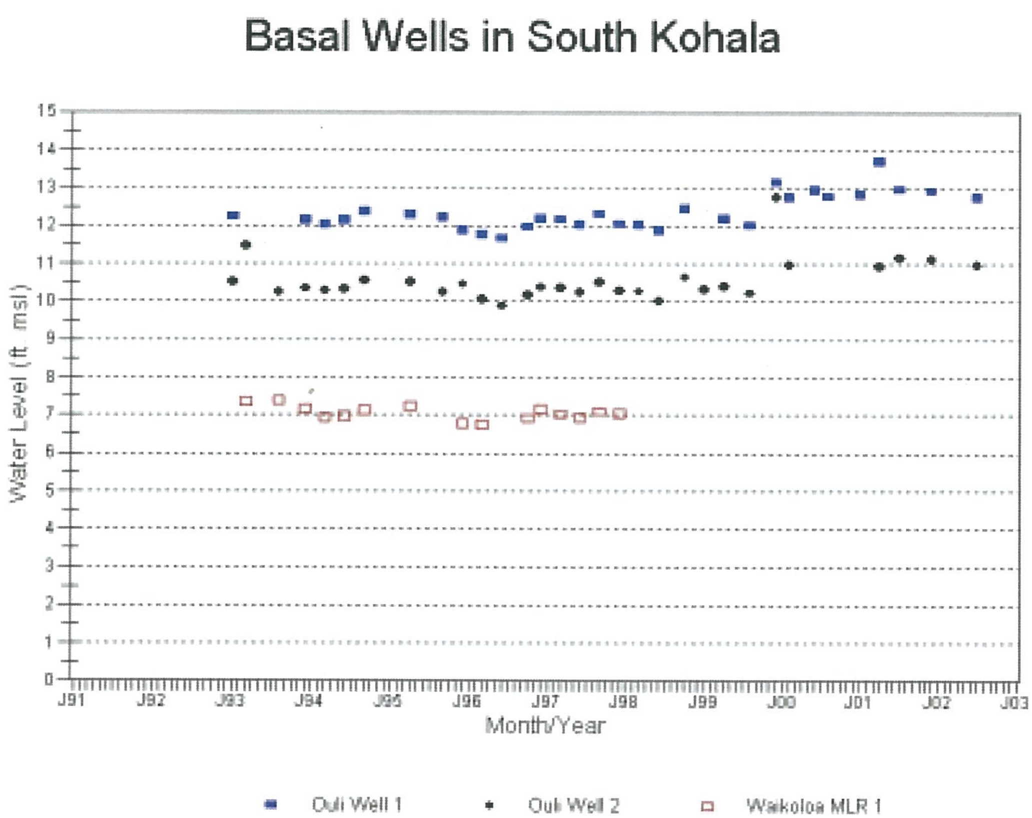

Figure 22. Water levels in the Lalamilo-Ouli Region.

5.2 High-Level Ground Water

High-level water level data collected by CWRM staff and USGS personnel are listed in Appendix A. Table 5 lists 18 wells. Of the 18 wells, only 7 wells have water level data spanning more than two measurements and for more than one year. As mentioned above, water levels in these wells are generally two types: 1) water levels standing several hundred feet above sea level that have shown a measured decrease over time; and 2) measured water levels in wells tens of feet above sea level, which exhibit a quasi-stable trend. The data presented will group the wells of each type.

The chloride concentration in the high-level wells is very low. Many of the sources produce water that is less than 10 mg/L chloride. The only exception is Huehue Ranch 5 which is located near the northwest rift zone of Hualalai, and the chemistry of the water pumped by this well has been affected by geothermal activity.

5.2.1 High-Level Wells Showing Declining Trends

One year after the monitoring program began, it became apparent that water levels in the high-level wells of Keahou-Kam 2 and 3 (3355-01,02), Honokohau (4158-02), and later, Hualalai-DWS (4258-02), were slowly declining (see Appendix A). A similar decline was observed in the USGS Kealakekua Obs. (3155-01) as USGS data became available. The rate of water level decline for these wells in ft/day is presented (over the period of measurement) in Table 5. The installation of pumps in the Hualalai-DWS and the DWS Halekii Well (near USGS Kealakekua Obs.) may affect the natural rate of decline; however, in Keahou-Kam 2 well, the rate of decline is not affected by nearby pumps. Taogoshi and others (2002) report that the measurement in the USGS Kealakekua Obs. well may be affected by the pumping well 50 ft. away; there is no information if the pumping well was on during the measurement. If the pump were on, then the drawdown from the pumping well would be observed in the USGS Kealakekua Obs. well. CWRM did not measure Hualalai-DWS when the pump was turned on.

To investigate whether pumping has affected the rate of decline of water levels in the Hualalai-DWS well, the water level difference between October 7, 1993 and December 10, 1997 (before the pump was installed July 1998) was 10.08 ft. Separation between measurements was 1,525 days. The resultant rate of decline is 0.0066 ft./day, which is greater than the rate of decline of 0.0053 ft./day (Table 5) for the entire period. For Keauhou-Kam 2 over approximately the same period (between December 7, 1993 and December 10, 1997 equals 1,464 days), the rate of decline is 0.0024 ft./day. This is slightly greater than the 0.0020 ft./day presented in Table 5. Therefore, the water level decline in Hualalai-DWS well does not seem to be affected by pumping.

Water level decline may be due to climatic factors. The Lanihau Rain Gage No. 515330 (State Key No. 68.20) is located above Keauhou at an elevation 1,530 ft., msl. This gage has operated continually since 1950. To examine climatic conditions for the period of record of water level data collection, total monthly rainfall at the Lanihau Gage is compared against the median monthly rainfall for 52 years of record. The deviation from the median monthly rainfall is either positive (above normal) or negative (below normal), and provides a way to determine whether monthly precipitation from 1991 to 2002 was drier or wetter than normal (also see Figure 15).

To compare the wells using the same scale, adjusted water levels are plotted in Figure 23 along with the departure from the monthly median rainfall. As seen in Figure 23, of the 140 months of record only 35 months or 25 percent of the time did Kailua-Kona experienced above normal rainfall conditions. Most of the rain occurred from 1996 through 1997. During this two-year period, 14 out of 24 months are positive. Other positive months are scattered throughout the record. Figure 23 clearly shows that during the 1996-97 wet period, water levels in all high-level wells either rose or remained flat. As drier conditions returned, water levels began to decline again. The record also shows that slight increases in water levels are associated wet months.

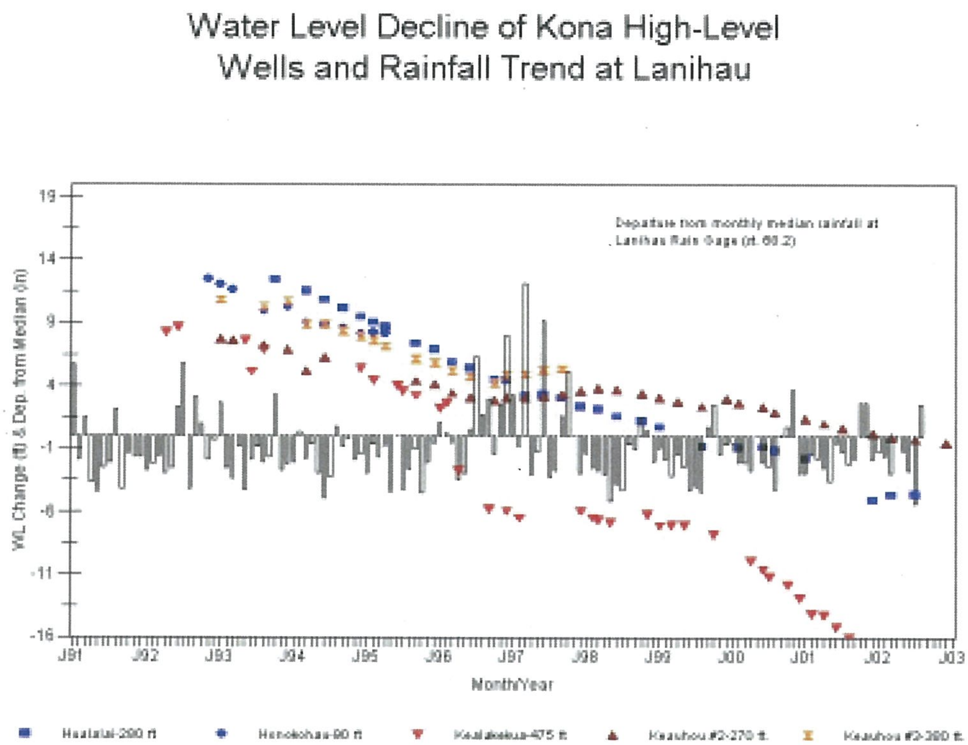

Figure 23. Comparison of water levels in high-level wells and deviation from median monthly rainfall at the Lanihau Gage

To assess the threshold of total monthly rainfall that produces positive change in the high-level wells, the 1996-97 period is evaluated. Table 8 lists the 14 months in that period that exceeded the monthly median amount. The data does not include intensity of rainfall, only totals. Even though the water levels only reflect instantaneous measurements for Keauhou-Kam 2 and 3, recharge from precipitation produced a positive change in the declining water levels after November 1996. The excess over the monthly median rainfall for those months listed in Table 8 from January 1996 to November 1996 was 15.39 in., while the excess between December 1996 and November 1997 was 39.56 in. For the two periods outlined above, the total rainfall for the first period was 49.04 in. and for the second period total rainfall was 64.40 in. In terms of percent, the excess rainfall in the first period is 31 percent of the total, while in the second period, the excess amounts to 61 percent of the total. Therefore to effect positive change in the aquifer, median monthly rainfall must be greater than 31 percent of total rainfall.

Table 8. Rainfall threshold Lanihau Rain Gage and water level changes in Keauhou-Kam wells 2 and 3.

Month and Year	Total Rainfall (in.)	Deviation Median Monthly (in.)	Keauhou-Kam 2 Water Level Date (ft., msl)	Keauhou-Kam 2 Change (ft.)	Keauhou-Kam 3 Water Level Date (ft., msl)	Keauhou-Kam 3 Change (ft.)
Jan. 1996	4.52	1.05				
Feb. 1996	2.77	0.25	3/5/96 (273.46)		3/5/96 (385.20)	
Jun. 1996	7.69	0.56	6/25/96 (273.09)	-0.37	6/25/96 (384.74)	-0.46
Jul. 1996	12.82	6.35				
Aug. 1996	7.19	1.66				
Sept. 1996	8.41	2.97	9/30/96 (272.87)	-0.22	9/30/96 (384.30)	-0.44
Nov. 1996	5.64	2.55				
Dec. 1996	10.60	8.00	12/4/96 (273.13)	+0.26	12/4/96 (384.87)	+0.57
Jan. 1997	6.74	3.27				
Mar. 1997	16.05	12.20	3/19/97 (273.13)	0	3/19/97 (384.96)	+0.09
Jun. 1997	16.36	9.23	6/17/97 (273.21)	+0.08	6/17/97 (385.28)	+0.32
Sept. 1997	6.33	1.62	9/9/97 (273.39)	+0.18	9/9/97 (385.38)	+0.10[1]
Oct. 1997	8.32	5.24				
Nov. 1997	2.62	0.015	12/10/97 (273.61)	+0.22		
Total Positive Change in Water Level:				+0.74		+1.08

[1] No access after September 1997.

As shown in Table 6, the relative volume of Keauhou-Kam 2 aquifer is about 1.5 times greater than the aquifer at Keauhou-Kam 3. It is assumed that the natural rate of ground-water recharge into the aquifers becomes greater due to the excess precipitation. If these aquifers are separated by geologic structure or have limited hydraulic connectivity, then the increase in recharge will show different water level changes. As pointed out earlier, Hirashima (1971) suggested that the recession constant, *b*, be used to determine the ease at which a tunnel can produce water or the ease for which recharge into the aquifer can occur over time. If *b* is large, then a tunnel can produce or recharge in a shorter period of time, than a smaller *b*. By analogy, the recession constant, *b*, computed for Keauhou-Kam 3 well is larger than Keauhou-Kam 2, therefore the rate of rise in the water level in the former well is greater than the latter. In fact, that is what was observed as presented in Table 8.

From Table 8, if the September 30, 1996 measurement is zero, and using the end date for the period as September 9, 1997, with 344 days between measurements, then the total rise in Keauhou-Kam 2 well is 0.52 ft and the total rise for Keauhou-Kam 3 is 1.08 ft. The straight-line rate of rise for that period is 0.0015 ft/day and 0.0031 ft./day for Keauhou-Kam 2 and Keauhou-Kam 3, respectively. Since the rate of water level rise in the Keauhou-Kam 3 well is twice as fast, then the aquifer volume is about half of Keauhou-Kam 2 aquifer. If the exponential equation is applied using the computed regression constants, b, as presented in Table 6, the calculated water level rise for the 344-day period is greater in both wells than the measured water level. The calculated water level gain is 0.66 ft. and 1.40 ft. in Keauhou-Kam2 and Keauhou-Kam 3, respectively. Figure 24 represents a conceptual model of the foregoing discussion.

Figure 25 is a correlation between water levels at Keahou-Kam 2 and 3. The correlation coefficient, R^2, is quite good at 0.94. Using the calculated best-fit equation for the line, the last measurement of 269.51 ft., msl taken at Keauhou-Kam 2 on December 3, 2002, would put the calculated water table elevation at Keauhou-Kam 3 at about 380.7± ft., msl, a loss of roughly 4.6± ft. since 1997.

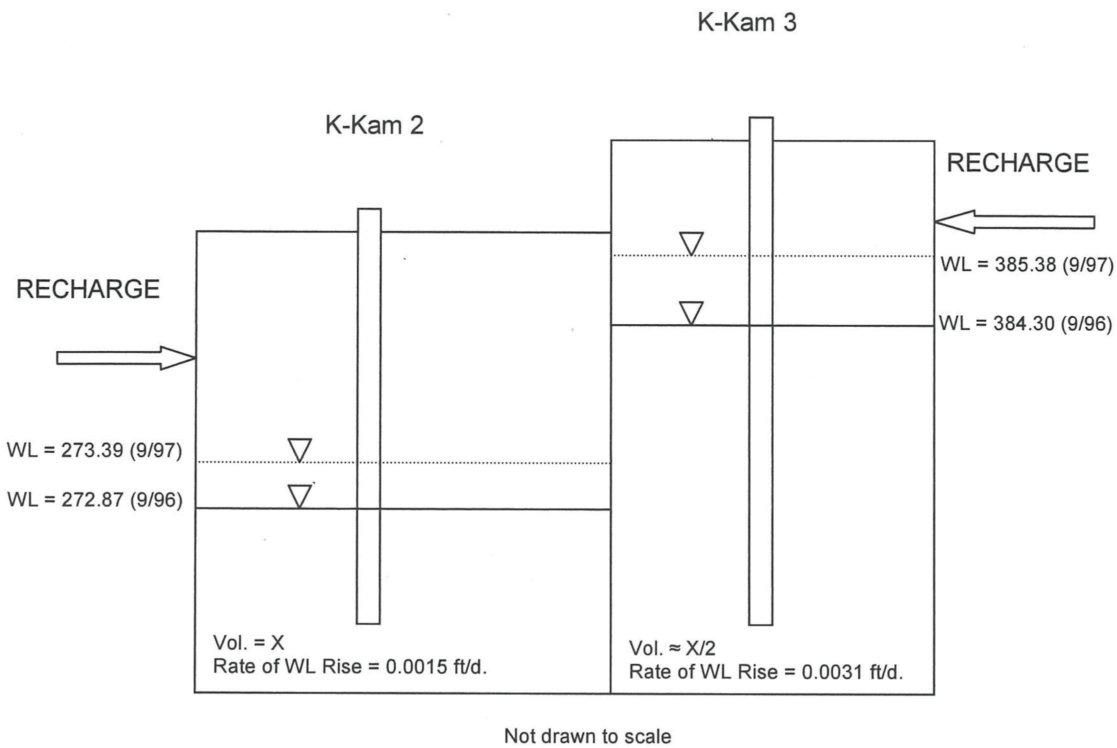

Figure 24. Conceptual model illustrating ground-water recharge into the high-level aquifers.

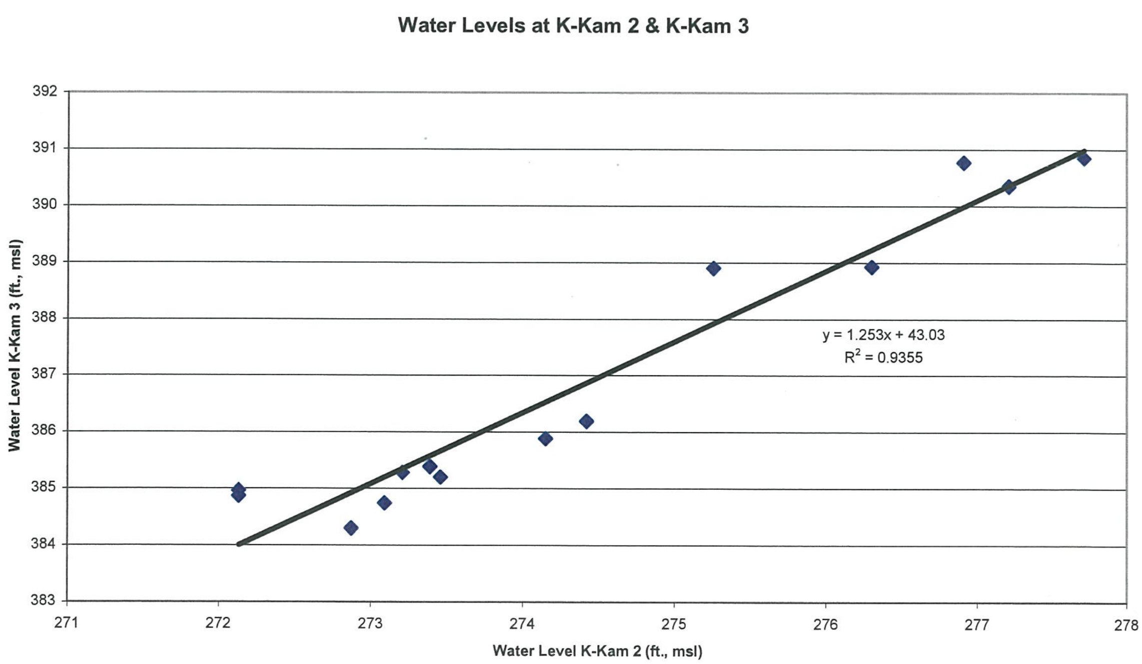

Figure 25. Water Level correlation between Keauhou-Kam 3 and Keauhou-Kam 2.

Because this group of wells exhibits declining water levels, and many of the wells were measured on the same day, a correlation between Keauhou-Kam 2 and the DWS Hualalai-DWS Well (4258-03) is presented as Figure 26. Prior to the wet period of 1996-1997, seven measurements show good correspondence having a R^2 value of 0.88. The above normal rainfall "reset" the water level in Keauhou-Kam 2, but after March 4, 1998 dry conditions once again prevailed. The correlation between the two wells after March 1998 is excellent with a R^2 value of 0.97.

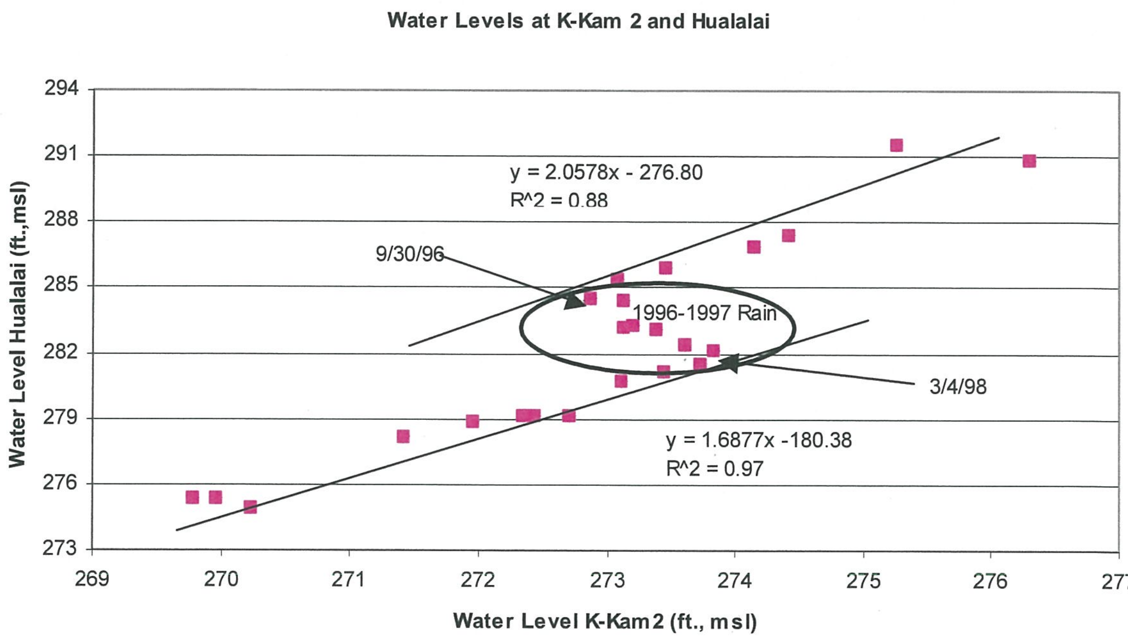

Figure 26. Water level correlation between Keauhou-Kam 3 and Hualalai-DWS.

Wells penetrating into the high-level aquifer indicate ground-water flow directions. As noted in Section 4.2, the Keopu region above Kailua-Kona appears to be a low point ("drain?") in the high-level aquifer flow system. Water levels rise both north and south of Keopu. Therefore, wells north of Keopu indicate that the ground-water flux is south and wells south of Keopu indicate that the ground-water flow direction is to the north. In spite of the apparent flow directions, subsurface geologic structure has a tremendous influence on ground-water flow. Undoubtedly, a fraction of the high-level ground water recharges adjacent basal aquifers, and as suggested earlier, some of the high-level water in Kalaoa may flow north to recharge the Kohanaiki (Kau)-Huehue Ranch wells' region.

CWRM drilled the Keopu Deep Monitor Well (3858-01) in 2001. The well is located at elevation 738± ft., msl and was designed to penetrate the basal aquifer to a bottom hole elevation of –574 ft., msl. This well is located down-gradient and seaward of the Douter-Coffee 1 Well (3957-04) and the State Keopu Well (3957-05). These wells have water levels of 43± ft. and 51± ft., msl, respectively. During construction of the Keopu Deep Monitor Well, the reported water level at casing depth (757 ft. ≈ -20 ft., msl) was 5± ft., msl. After completion, a water level measurement on December 4, 2001 was 27.26 ft., msl. When a water level transducer was installed into a sounding or chase tube, set at a depth of 752 ft., the water level in the tube was 4± ft., msl. The two different water levels indicate that the well penetrates zones where ground water enters the well bore under artesian pressure. The well represents an average water level throughout the water column, whereas, the chase tube water level measures only the water level (like a piezometer) at the top of the aquifer. If the Keopu region is indeed a zone where high-level ground water discharges into the basal aquifer, then the Keopu Deep Monitor Well is evidence that high-level ground-water flow is occurring at depth.

5.2.2 High-Level Wells Showing Quasi-Stable Trends

There are four wells that have water levels between 40 and 50 ft., msl in the Keopu area. These wells (shown in Table 5) are the Keopu-Haseko well (3957-01), USGS Komo Observation well (3957-02), Douter-Coffee 1 (3957-03), and the State Keopu well (3957-04). The USGS Komo Observation well is monitored continuously using a pressure transducer. Mr. Daniel Lum is currently monitoring the Keopu-Haseko Well using pressure transducer as an observation well during the completion of the State Keopu Well. Continuous water level measurements should be taken in other wells in the area.

The water level in the USGS Komo Observation well fluctuated about 1.5 ft. throughout the period of record (see Appendix A). Continuous water levels, expressed as an average daily water level, show water level changes reminiscent of drawdown and recovery curves as recorded during aquifer tests. However, these periods are long-term lasting from six months to a year. Figure 27 presents a graph of the average daily water levels from May 2000 to April 2003. As seen in the graph, there is a slow recovery of 1.2 ft. extending from May 2001 to November 2001. From February 2002 to August 14, 2002 water levels declined. On August 15, 2002, the water level in the well started to rise steeply to approximately 42.4 ft., msl.

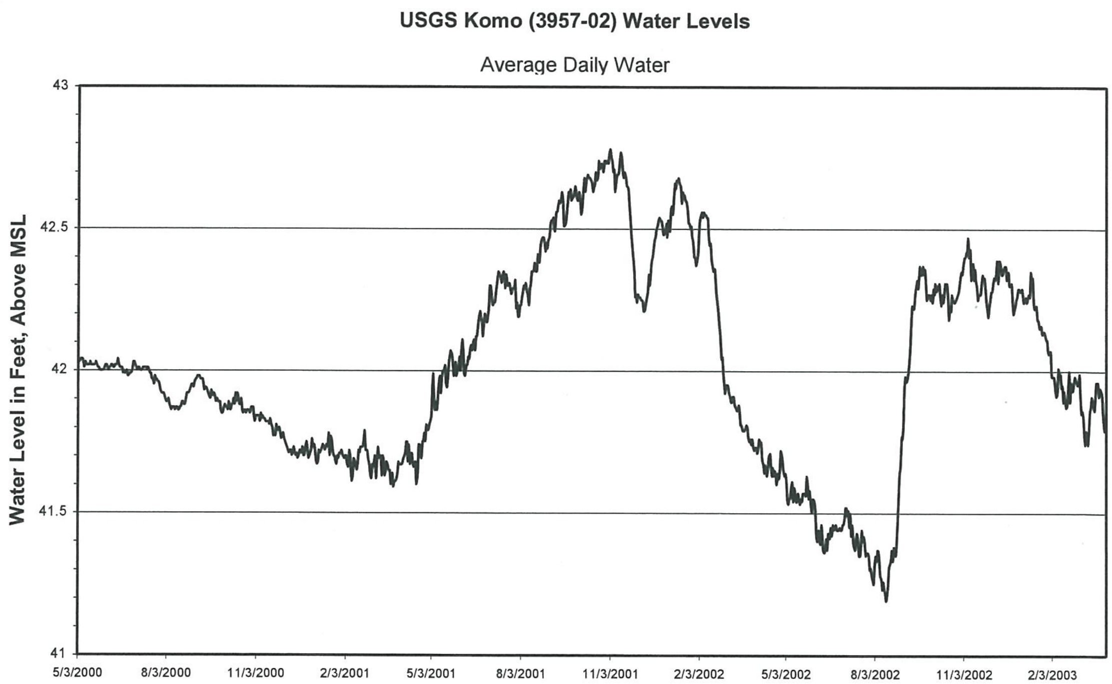

Figure 27. Average daily water levels in the USGS Komo Observation Well.

Water levels in this chart reflect rainfall conditions in the area. Figure 27 mimics in a more robust way the water level graph presented for the Kahaluu Deep Monitor well (Figure 6) and the rainfall monthly pattern at Lanihau Gage No. 515330 as illustrated in Figure 7.

The average daily water levels in Keopu-Haseko well are presented in Figure 28 (Daniel Lum, personal communication, August 13, 2003). The period of record is from

December 1, 2001 to the present time. Contrary to the water levels observed in the USGS Komo well, Keopu-Haseko well appears to be slowly declining, though recovering slowly June 11, 2003.

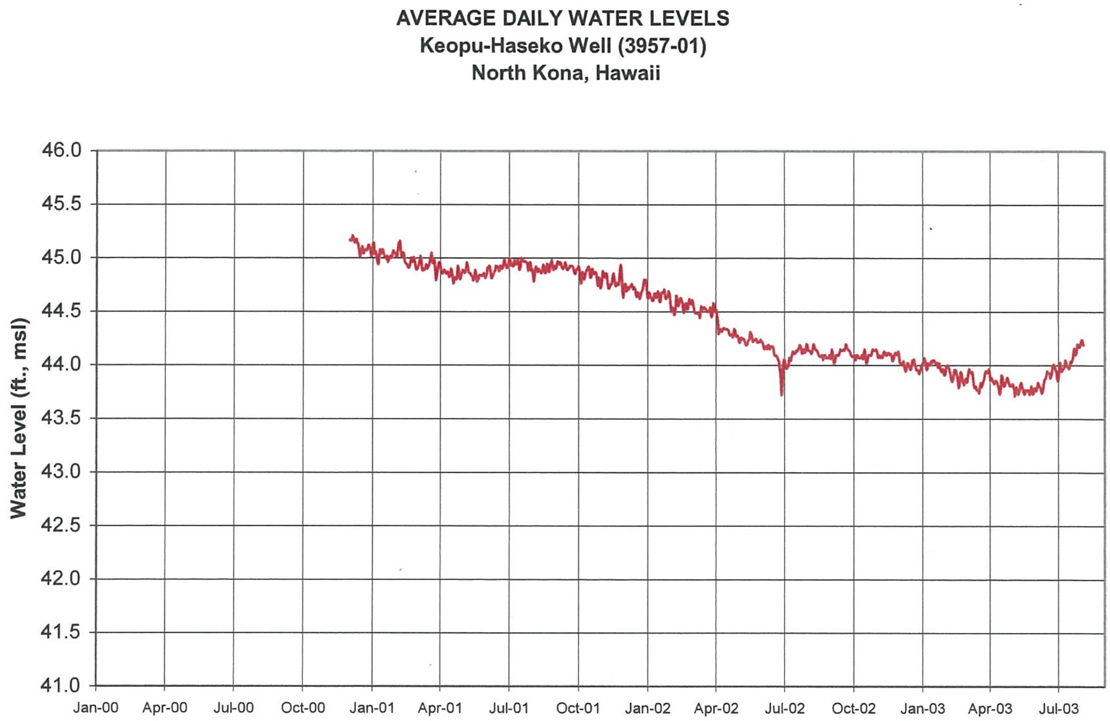

Figure 28. Average daily water levels in Keopu-Haseko well (from Daniel Lum, Water Resource Associates).

Finally, the Huehue Ranch Well 5 (4558-02) is located adjacent to Puhia Pele, a volcanic spatter cone that erupted during the 1801 activity of Hualalai. Water levels were measured in this well from 1997-2002. The average water level during this time is 23.30 ft., msl. Due to the well's location along the northwest rift zone, buried volcanic dikes are impounding this aquifer. Despite the presumed presence of dikes, a constant rate aquifer test, performed over four days, did not show the presence of dikes. The test was run at 550 gpm with a drawdown of 6.2± ft. (Waimea Water Services and Island Resources, 1992). A pump was recently installed.

Figure 29 presents the water level data in graphical form. The water levels change very little.

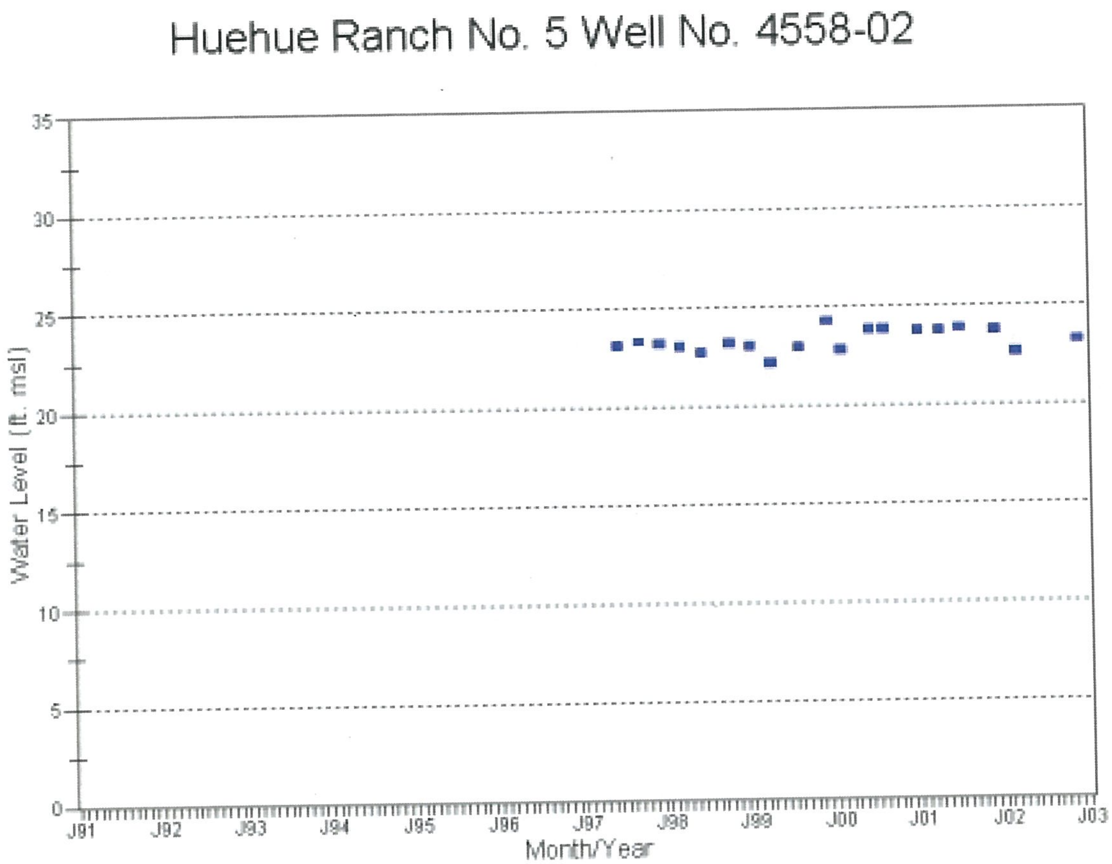

Figure 29. Water levels in Huehue Ranch 5.

As seen in the data, the water varies only a foot about the 23± ft., msl elevation. The water level in Huehue Ranch 5 does not correlate well with the basal Huehue Ranch 1, suggesting that water level changes are due to a different ground-water flow system.

Water chemistry indicates that there may be a geothermal influence (Thomas, 1986). Reported chlorides were 31 mg/L, but the sulfate concentration was 200 mg/L (Waimea Water Services and Island Resources, 1992). In addition, the high sulfate concentration probably contributed to a pH value that was reported at 6.08. In terms of corrosivity the water is considered "moderately aggressive." There was no report on the silica concentration. Present conditions indicate that the Total Dissolved Solids (TDS) are 950 mg/L with the chloride content at 85 mg/L. In order for this water to be used, softeners will need to be added (Stephen Stephen P. Bowles, personal communication, 2003).

6. Conclusions

As pointed out in the first paragraph of this report, what began as competition among developers, landowners, and public utilities for the water resources of West Hawaii became a means to gather needed ground-water data to understand the resource, and to provide accurate ground-water information to the CWRM, landowners, and consultants alike. The importance of collecting long-term baseline data cannot be over emphasized. These data become the "eyes" for gaining insight into the West Hawaii ground-water resources. This report is based upon 171 individual measurements in the high-level wells and 636 individual measurements in the basal wells.

Over the period of record covered by this report the following conclusions are reached:

1. The data strongly suggest a slow decline of water levels in some of the high-level wells and an apparent relationship to water level decline and climatic conditions as recorded in the Lanihau and Huehue Ranch rain gages. Future wells drilled into this resource should be used, prior to pump installation, as observation wells to verify the trends documented in this report.

2. The data suggest that the high-level wells tap interconnected, though structurally bounded, aquifers whose rate of water level decline is inversely proportional to its volume. Future well drilling for high-level potable sources must include accurate, well-designed aquifer tests that will aid in the determination of geologic boundaries to provide information on the geometry of the aquifer.

3. The data suggest that there may be more than geological mechanism that created the high-level aquifer.

4. The data suggest that there is a water level pattern as observed in the high-level wells with Keopu being the "drain" for the ground-water flow system. That the ground-water flux south of Keopu is to the north, and north of Keopu, the ground-water flow is to the south.

5. Some high-level wells do exhibit quasi-stable water levels, and show little variation over time. Use of long-term water level transducers in these wells should continue in conjunction with long-term water level transducers in those wells that show water level decline. Real time correlation between water levels in the wells with climatic conditions measured at Lanihau Rain Gage will provide better insight into the behavior of the potable high-level aquifer.

6. The data suggest the influence of climate over long-term trends in the basal aquifers.

7. The strong correlation between well pairs will aid in predicting a water level if only one of the wells can be measured.

8. The data suggest the variability of the ground-water flow direction in a shallow basal lens system, as can be seen at the West Hawaii Landfill, is translatable to other areas.

9. The low ground-water gradients suggest a highly permeable basal coastal aquifer where basaltic lavas comprise the aquifer, and this finding is supported by tidal analysis. The composition of the lava flows determines its permeability, and in turn, the ground-water gradient.

10. These data will become calibration targets for future numerical and analytical ground-water models and will aid in the site selection for new wells.

Because this area is still experiencing tremendous growth in population, hotel construction, and the development of large acreages of land, the ground-water monitoring network will continue to provide knowledge, and will be the basis for better management of the resource by both public and private entities. The ground-water monitoring network described above is in actuality a partnership between government and private entities. As new wells are drilled, CWRM is allowed access to measure and sample the resource. These measurements are available to owners and consultants alike.

It is recommended that this monitoring work continue, and that new hydrological and geological information (i.e. drill cuttings, water samples, water level measurements) be analyzed and incorporated into current understanding of West Hawaii. With these new data, updating this report should occur every five years.

7. Acknowledgements

This study would not have been possible without the support of the Commission and CWRM staff. Those staff members who, over the years, spent long hours in the field collecting water level and chloride data are Mitchell Ohye, Neal Fujii, Lenore Nakama, and Kevin Gooding. Others who helped in the field are Ryan Imata, Richard Jinnai, and Dean Uyeno. Ingrid Kunimura produced many of the figures in this report.

Access to Hawaii DWS facilities where the USGS Komo well, Hualalai-DWS well, and CWRM's Kahaluu Deep Monitor well are located was made possible by Mr. Richard "Junior" Ono. From the private sector, Messrs. Stephen Bowles and John Stubbart of Waimea Water Services provided access to the Huehue Ranch, Kukio, and Kaupulehu wells. Mr. Bowles also provided the author with well logs, interpretations of geology, benchmarks for private wells, and a copy of Dr. Duate's PhD dissertation. Mr. Tom Nance of Tom Nance Water Resource Engineering provided the author with benchmarks and information regarding the Keauhou and Keauhou-Kam wells. Mr. Daniel Lum of Water Resource Associates provided the author with geologic logs of various wells, and water level data for the Keopu-Haseko well. Mr. John Mink discussed aspects of the geology of West Hawaii with the author over the years. In addition, insightful conversations with Drs. David Clague, Scientist-in-Charge (1991-96) at the USGS' Hawaiian Volcano Observatory (HVO), and James Kauahikaua, volcanologist at HVO, provided the author with a broader understanding of the regional geology and petrology of Hualalai, which aided in the presentation of this report.

Access to the Waikoloa wells was made available through West Hawaii Utilities and Mr. Stephen Green. Waste Management Hawaii, Inc.'s (West Hawaii Landfill) Mr. Steve Cassulo provided access and information about their monitor wells. And finally, Mr. Norman Ah Hee of Mauna Lani Resort provided access keys to the Mauna Lani wells.

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Appendix A

Water Level Data

High-Level Wells

USGS Kealakekua Obs. Well No. 3155-01

		Remarks
9/6/91	490.00	All water level data collected by USGS.
4/16/92	483.30	
6/16/92	483.66	
6/14/93	480.14	
8/4/93	481.89	
12/7/94	480.39	
3/23/95	479.47	
6/12/95	479.07	
7/13/95	478.65	
9/21/95	478.24	
1/2/96	477.26	
12/18/97	469.06	
2/6/98	468.55	
3/24/98	468.38	
5/29/98	468.17	
11/12/98	468.81	
1/21/99	467.94	
3/19/99	467.98	
5/27/99	467.99	
7/21/99	467.50	
10/25/99	467.25	
4/12/00	465.15	
6/6/00	464.46	
7/20/00	463.89	
10/18/00	463.24	
12/18/00	462.15	
2/27/01	460.92	
4/27/01	460.18	
6/12/01	459.81	
8/17/01	459.07	

USGS Kainaliu Obs. Well No. 3255-01

		Remarks
9/6/91	420.13	All water level data collected by USGS.
6/6/00	406.66	

State Kainaliu Test Well No. 3255-02

		Remarks
8/4/93	306.00	Oil from pump test in well, measurement difficult.
3/1/94	303.04	

Keauhou-Kam 2 Well No. 3355-01

		Remarks
3/12/91	278.09	
1/27/93	277.71	
3/31/93	277.61	
8/4/93	277.21	
12/7/93	276.91	
3/1/94	275.26	
6/13/94	276.30	
9/20/95	274.42	
12/5/95	274.15	
3/5/96	273.46	
6/25/96	273.09	
9/30/96	272.87	
12/4/96	273.13	
3/19/97	273.13	
6/17/97	273.21	
9/9/97	273.39	
12/10/97	273.61	
3/4/98	273.84	
6/23/98	273.73	
10/13/98	273.44	
1/25/99	273.11	
4/26/99	272.81	
8/3/99	272.44	
12/6/99	273.03	
2/22/00	272.70	
6/5/00	272.35	
8/29/00	271.96	
1/9/01	271.41	
4/24/01	271.04	
7/24/01	270.70	
12/4/01	270.23	
3/19/02	269.96	
7/19/02	269.78	
12/3/02	269.51	

Keauhou-Kam 3 Well No. 3355-02

		Remarks
1/27/93	390.85	
8/4/93	390.35	
12/7/93	390.77	
3/1/94	388.90	
6/13/94	388.92	
9/8/94	388.35	
12/7/94	387.95	
2/6/95	387.65	
4/26/95	387.17	
9/20/95	386.19	
12/5/95	385.88	
3/5/96	385.20	
6/25/96	384.74	
9/30/96	384.30	
12/4/96	384.87	
3/19/97	384.96	

6/17/97	385.28	
9/9/97	385.38	Access to well is difficult, property is overgrown.

Keauhou-Kam 4 Well No. 3355-03

		Remarks
3/1/94	211.46	
6/13/94	221.96	
9/8/94	222.46	Access difficult; residual oil in well from pump test.

USGS Komo Obs. Well No. 3957-02

		Remarks
9/6/91	42.20	USGS measurment.
1/2/93	42.80	
9/9/97	42.45	
12/10/97	41.47	
3/4/98	41.34	
6/23/98	40.95	
10/13/98	41.42	
1/25/99	41.03	
4/26/99	40.70	Handar water level transducer installed 4/27/99
12/6/99	42.24	All subsequent water levels are instaneous readings from
2/22/00	42.03	Handar transducer.
6/5/00	42.03	
8/29/00	41.96	
1/9/01	41.70	
4/24/01	41.75	
7/24/01	42.33	
12/4/01	42.17	
3/19/02	41.81	
7/16/02	41.47	
12/3/02	42.36	

Honokohau Well No. 4158-02

		Remarks
11/17/92	102.50	
1/27/93	102.09	
3/31/93	101.63	
8/4/93	99.99	
12/7/93	100.31	
3/1/94	99.09	
6/13/94	99.89	
9/7/94	98.64	
12/7/94	98.15	
2/6/95	98.26	
4/26/95	98.19	Pump installed.

Hualalai Well No. 4258-03

		Remarks
8/4/93	190.70	
10/7/93	292.44	Drilled 100 ft. deeper, water rose 100± ft.

3/1/94	291.54	
6/13/94	290.85	
9/7/94	290.19	
12/7/94	289.49	
2/6/95	289.09	
4/26/95	288.65	
9/20/95	287.37	
12/5/95	286.90	
3/5/96	285.91	
6/25/96	285.39	
9/30/96	284.53	
12/4/96	284.44	
3/19/97	283.18	
6/17/97	283.31	
9/9/97	283.07	
12/10/97	282.36	Start using chase tube for measurement
3/4/98	282.15	
6/23/98	281.56	
10/13/98	281.19	Pump work completed in July 1998. Water level measurements only taken when pump is off.
1/25/99	280.73	
8/3/99	279.19	
2/22/00	279.11	
6/5/00	279.13	
8/29/00	278.86	
1/9/01	278.22	
12/4/01	274.91	
3/19/02	275.37	
7/16/02	275.38	

Huehue 5 Well No. 4558-02

		Remarks
6/17/97	23.12	
9/9/97	23.32	
12/9/97	23.17	
3/4/98	23.06	
6/23/98	22.75	
10/13/98	23.22	
1/25/99	23.05	
4/26/99	22.18	
8/3/99	22.96	
12/6/99	24.28	
2/22/00	22.82	
6/5/00	23.83	
8/29/00	23.85	
1/9/01	23.76	
4/24/01	23.78	
7/24/01	23.87	
12/4/01	23.77	
3/19/02	22.66	
12/3/02	23.24	Pump installed, chase tube measurment.

Basal Wells

Keauhou B Well No. 3456-01

		Remarks
11/17/92	1.96	
1/27/93	3.15	
3/31/92	2.93	
8/4/93	2.85	
12/7/93	2.87	
3/1/94	2.26	
6/13/94	2.48	
9/7/94	2.57	
12/7/94	3.01	
2/6/95	2.59	
4/26/95	2.59	
7/13/95	2.68	
9/20/95	2.49	
12/5/95	2.75	
3/5/96	2.43	
6/25/96	1.96	Access to well becoming increasingly difficult.

Keauhou A Well No. 3457-02

		Remarks
12/8/93	2.75	
3/2/94	2.63	
9/7/94	3.44	
12/7/94	3.41	
2/6/95	2.88	
4/26/95	3.17	
7/13/95	3.16	
9/20/95	2.94	
12/5/95	3.24	
3/5/96	2.85	
6/25/96	2.48	
9/30/96	3.37	
12/4/96	3.31	
3/19/97	2.81	
6/17/97	2.50	
9/9/97	3.30	
12/10/97	3.34	
3/4/98	3.05	
6/23/98	2.35	
10/13/98	3.19	
1/25/99	3.16	
4/26/99	2.79	
8/3/99	3.20	
12/6/99	4.04	
2/22/00	3.75	
6/5/00	3.31	
8/29/00	3.49	
1/9/01	3.95	
4/24/01	3.20	
7/24/01	3.74	
12/4/01	4.13	
3/19/02	3.51	
7/16/02	3.18	

12/3/02	3.74	

Kahaluu Deep Monitor Well No. 3457-04

		Remarks
1/9/01	2.21	Instaneous measurement using a water level sounder.
4/24/01	1.61	Handar transducer install November 2000.
7/24/01	2.12	
12/4/01	2.78	
3/19/02	1.99	
7/16/02	1.80	
12/3/02	2.02	

Pahoehoe Well No. 3657-02

		Remarks
1/29/93	5.23	
4/1/93	5.23	
8/6/93	4.99	
12/8/93	5.10	
3/2/94	4.79	
6/14/94	4.81	
9/8/94	4.83	
12/7/94	4.94	
2/6/95	4.76	
4/26/95	5.02	
12/5/95	4.82	
12/10/97	4.83	Access to well site increasingly difficult.

Kaloko Irr. 1 Well No. 4160-01

		Remarks
11/17/92	2.70	
1/27/93	2.81	
3/31/93	2.59	June 1993 well bore obstructed by garbage.

Kaloko Irr. 2 Well No. 4160-02

		Remarks
12/7/93	2.54	
3/1/94	1.98	
6/13/94	2.08	
9/7/94	2.14	
12/7/94	2.35	
2/6/95	2.04	
4/26/95	2.45	
9/20/95	3.59	
12/5/95	2.45	
3/5/96	3.21	
6/25/96	3.00	
9/30/96	3.05	
12/4/96	3.53	Access road blocked by large boulders and rubbish.

Ooma Test Well No. 4262-01

		Remarks
1/27/93	1.50	Influenced by ocean tides.
3/31/93	1.97	
8/4/93	2.13	
12/7/93	1.69	
3/1/94	0.81	
6/13/94	2.31	
9/7/94	1.43	
12/7/94	2.14	
2/6/95	1.13	
4/26/95	1.59	
7/13/95	1.56	
9/20/95	2.26	
12/5/95	1.63	
3/5/96	1.45	
6/25/96	1.64	
9/30/96	1.30	
12/4/96	1.64	
3/19/97	1.75	
6/17/97	2.14	
9/9/97	2.03	
12/9/97	1.65	
3/4/98	1.12	
6/23/98	1.83	
10/13/98	2.24	
1/25/99	1.48	
4/26/99	1.72	
8/3/99	1.62	
12/6/99	1.68	
2/22/00	1.03	
6/5/00	1.10	
8/29/00	2.00	
1/9/01	1.44	
4/24/01	1.29	
7/24/01	1.45	
12/4/01	1.41	
3/19/02	1.24	
7/16/02	1.62	
12/3/02	1.76	

Kalaoa Irr. Well No. 4360-01

		Remarks
10/15/92	2.00	One of the best basal baseline wells in the network.
11/17/92	2.72	
1/27/93	2.70	
3/31/93	2.75	
8/4/93	2.37	
12/7/93	2.62	
3/1/94	2.14	
6/13/94	2.26	
9/7/94	2.30	
12/7/94	2.43	
2/6/95	2.22	
4/26/95	2.54	
7/13/95	2.38	
9/20/95	2.50	
12/5/95	2.31	

3/5/96	2.21
6/25/96	1.99
9/30/96	2.18
12/4/96	2.53
3/19/97	2.15
6/17/97	1.98
9/9/97	2.58
12/9/97	2.52
3/4/98	2.26
6/23/98	1.76
10/13/98	2.34
1/25/99	2.31
4/26/99	1.99
8/3/99	2.33
12/6/99	2.04
2/22/00	2.62
6/5/00	2.41
8/29/00	2.67
1/9/01	2.67
4/24/01	2.55
7/24/01	2.65
12/4/01	2.76
3/19/02	2.66
7/16/02	2.54
12/3/02	2.72

Kau (Kohanaiki) 1 Well No. 4458-01

		Remarks
9/6/91	9.85	
10/15/92	9.87	
11/18/92	9.64	
1/28/93	10.06	
4/1/93	10.14	
8/5/93	9.89	
12/8/93	9.79	
3/2/94	9.64	
6/14/94	9.75	
9/8/94	10.02	
4/27/95	10.10	
9/20/95	9.87	
12/6/95	9.76	
3/6/96	9.38	
6/26/96	9.27	
10/1/96	9.57	
12/5/96	9.74	
3/20/97	9.61	
6/18/97	9.56	
9/10/97	9.82	
12/9/97	9.60	
3/4/98	9.54	
6/24/98	9.14	
10/14/98	9.64	
1/25/99	9.52	
4/26/99	9.38	
8/4/99	9.38	
12/7/99	10.74	
2/23/00	10.23	
6/6/00	10.43	
8/30/00	10.02	
1/11/01	9.05	

4/26/01	9.41	
7/26/01	10.07	Construction in the vicinity of the well makes access difficult.

Kau (Kohanaiki) 2 Well No. 4458-02

		Remarks
9/6/91	10.19	
10/15/92	10.17	
11/18/92	10.23	
1/28/93	9.97	
4/1/93	10.54	
8/5/93	10.34	
12/8/93	10.28	
3/2/94	10.15	
6/14/94	10.23	
9/8/94	10.30	
4/27/95	10.50	
9/20/95	10.28	
12/6/95	10.14	
6/26/96	9.66	
4/26/99	9.73	
8/30/00	10.78	
12/6/01	10.61	
3/21/01	10.61	
7/16/02	10.50	
12/5/02	10.65	Pump being installed

Huehue Ranch 1 Well No. 4559-01

		Remarks
4/1/93	8.67	
8/5/93	8.51	
12/8/93	8.44	
3/2/94	8.20	
6/14/94	8.23	
9/8/94	9.02	
9/20/95	8.39	
125/95	7.37	
3/5/96	7.80	
6/25/96	7.70	
9/30/96	8.48	
12/4/96	8.27	
3/19/97	7.06	
6/17/97	7.95	
9/9/97	8.24	
12/9/97	8.17	
3/4/98	7.90	
10/13/98	8.19	
1/25/99	7.86	
4/26/99	7.73	
8/3/99	7.91	
12/6/99	10.04	
2/22/00	9.42	
6/5/00	9.60	
8/29/00	8.86	
1/9/01	8.77	
4/24/01	8.77	
7/24/01	8.89	

12/4/01	8.74
3/19/02	8.65
7/16/02	9.53
12/3/02	9.53

Huehue Ranch 3 Well No. 4558-01

		Remarks
11/17/92	6.14	Measurement by airline
1/28/93	6.94	Measurement by airline
8/5/93	6.25	Measurement by airline Pump in operation.

Kaupulehu 1 Well No. 4658-01

		Remarks
11/17/92	5.82	
1/28/93	5.69	
4/1/93	5.94	
8/5/93	4.53	
12/8/93	5.63	
3/2/94	5.32	
6/14/94	5.42	
9/8/94	5.47	
2/6/95	4.24	
4/27/95	5.60	
3/5/96	5.10	Pump installed. Use chase tube for measurement.

Kaupulehu Irr. 1 Well No. 4757-01

		Remarks
11/17/92	1.99	
1/28/93	1.94	
4/1/93	2.74	
8/5/93	1.74	
12/8/93	1.81	
3/2/94	0.56	Unusually low.
6/14/94	1.67	
4/27/95	2.93	
12/4/96	2.83	Pump installed.

Kukio Irr. 1 Well No. 4759-01

		Remarks
10/15/92	1.56	
11/18/92	1.54	
1/28/93	1.46	
4/1/93	1.67	
8/5/93	1.29	
12/8/93	1.47	
3/2/94	1.07	
6/14/94	1.20	
9/8/94	1.22	
9/20/95	1.39	

12/5/95	1.23	
3/5/96	0.95	
6/25/96	0.97	
9/30/96	1.18	
12/4/96	1.49	
3/19/97	1.15	
6/17/97	1.11	
9/9/97	1.42	
12/9/97	1.55	
3/4/98	1.15	
8/3/99	1.26	
2/22/00	1.34	
6/5/00	1.43	
8/29/00	1.71	Pump installed, reference benchmark lost.

Kukio Irr. 2 Well No. 4759-02

		Remarks
10/15/92	1.54	
11/18/92	1.57	
1/28/93	1.47	
4/1/93	2.14	
8/5/93	1.79	
12/8/93	1.97	
3/2/94	1.58	
6/14/94	1.69	
9/8/94	1.72	
8/3/99	1.73	
2/22/00	1.53	
6/5/00	1.57	
8/29/00	1.81	Pump installed. Pump on most of the time.

Kukio Irr. 3 Well No. 4759-03

		Remarks
10/15/92	1.58	
11/18/92	1.58	
1/28/93	1.52	
4/1/93	1.66	
8/5/93	1.30	
12/8/93	1.49	
3/2/94	1.10	
6/14/94	1.20	
9/8/94	1.35	
9/20/95	1.35	
12/5/95	1.27	
3/5/96	0.96	
6/25/96	0.95	
9/30/96	1.20	
12/4/96	1.49	
3/19/97	1.15	
6/17/97	1.04	
9/9/97	1.41	
12/9/97	1.52	
3/4/98	1.19	
6/23/98	0.69	
10/13/98	1.49	
1/25/99	1.99	

4/26/99	0.86	
8/3/99	1.26	
12/6/99	1.93	
2/22/00	1.40	
6/5/00	1.45	
8/29/00	1.69	Pump installed. Pump on most of the time.

Kiholo Well No. 4953-01

		Remarks
12/9/93	2.35	
3/3/94	2.04	
6/15/94	2.17	
9/9/94	2.12	
4/27/95	2.42	
12/6/95	2.18	
6/26/96	2.19	
10/1/96	1.96	
12/5/96	2.67	
3/20/97	2.08	
6/18/97	2.05	
9/10/97	2.11	
12/9/97	2.24	
6/24/98	1.69	
1/26/99	2.07	
4/26/99	1.87	
8/4/99	2.02	USGS installed pressure transducer.

Puu Anahulu Well No. 5347-01

		Remarks
12/4/96	7.50	
3/20/97	7.55	
6/18/97	7.33	
12/9/97	7.29	
3/5/98	7.24	
6/24/98	6.94	
10/14/98	7.46	
1/26/99	7.14	
4/27/99	7.31	
8/4/99	7.25	
12/7/99	8.52	
2/23/00	8.11	
6/6/00	8.22	
8/30/00	8.13	
4/26/01	8.10	
7/26/01	8.29	
12/6/01	8.22	
3/21/02	8.08	Well sabotaged between March 2002 and July 2002.

West Hawaii Landfill MW 1 No. 5353

		Remarks
6/26/96	2.97	
10/1/96	2.05	
12/5/96	2.03	

3/20/97	1.67
6/18/97	1.81
9/10/97	2.04
12/9/97	1.99
3/5/98	1.69
10/14/98	2.16
1/26/99	1.75
4/27/99	1.46
8/4/99	1.89
12/6/99	2.14
2/23/00	1.74
6/6/00	1.61
8/30/00	1.92
4/26/01	1.58
7/26/01	1.93
12/6/01	2.04
3/21/02	1.79
7/18/02	1.75
12/5/02	2.08

West Hawaii Landfill MW 2 No. 5353

		Remarks
6/26/96	2.94	
10/1/96	1.94	
12/5/96	2.01	
3/20/97	1.65	
6/18/97	1.77	
9/10/97	2.04	
12/9/97	2.00	
3/5/98	1.66	
10/14/98	2.10	
1/26/99	1.80	
4/27/99	1.44	
8/4/99	1.91	
12/6/99	2.11	
2/23/00	1.62	
6/6/00	1.46	
8/30/00	1.88	
4/26/01	1.56	
7/26/01	1.85	
12/6/01	2.03	
3/21/02	1.78	
7/18/02	1.75	
12/5/02	2.07	

West Hawaii Landfill MW 3 No. 5352

		Remarks
6/26/96	2.37	
10/1/96	1.69	
12/5/96	1.77	
3/20/97	1.35	
6/18/97	1.55	
9/10/97	1.73	
12/9/97	1.16	
3/5/98	1.37	
10/14/98	1.90	

1/26/99	1.46
4/27/99	1.20
8/4/99	1.67
12/6/99	1.79
2/23/00	1.26
6/6/00	1.24
8/30/00	1.54
4/26/01	1.23
7/26/01	1.59
12/6/01	1.74
3/21/02	1.45
7/18/02	1.48
12/5/02	1.76

Waikoloa 3 Well No. 5546-02

		Remarks
1/27/93	6.17	
3/31/93	6.24	
8/5/93	6.19	
12/7/93	6.14	
3/1/94	6.03	
6/13/94	5.96	
9/7/94	6.13	
4/27/95	6.23	
9/21/95	6.10	
12/6/95	6.16	
3/6/96	6.07	
6/26/96	5.87	
10/1/96	6.25	Pump installed.

Waikoloa Irr. 4 Well No. 5552-01

		Remarks
1/27/93	2.28	
3/31/93	2.21	
8/5/93	1.99	
12/7/93	2.28	
3/1/94	1.81	
6/13/94	1.89	
9/7/94	1.82	
4/27/95	2.16	
12/6/95	1.64	
6/26/96	1.80	
10/1/96	1.96	
12/5/96	2.35	
3/20/97	1.95	
12/9/97	2.37	
3/5/98	2.00	
6/24/98	1.45	
10/14/98	2.39	
1/26/99	2.07	
8/4/99	2.20	
12/6/99	2.37	
2/23/00	1.94	
6/6/00	1.88	
8/30/00	2.17	
1/11/01	2.38	

4/26/01	1.91	
7/26/01	2.24	
12/6/01	2.23	
3/21/02	2.08	
7/18/02	1.92	
12/5/02	2.40	Ongoing measurements

Waikoloa Irr. 5 Well No. 5551-01

		Remarks
1/27/93	2.23	
3/31/93	2.59	
8/5/93	2.04	
12/7/93	2.33	
3/1/94	1.87	
6/13/94	1.92	
9/7/94	1.99	
4/27/95	2.22	
12/6/95	1.69	
3/6/96	1.78	
6/26/96	1.85	
10/1/96	2.02	
12/5/96	2.39	
3/20/97	2.00	
6/18/97	2.05	
12/9/97	2.45	
3/5/98	2.06	
10/14/98	2.44	
1/26/99	2.12	
4/27/99	1.81	
8/4/99	2.27	
2/23/00	2.02	
6/6/00	1.99	
8/30/00	2.28	
7/26/01	2.23	
12/6/01	2.32	
3/21/02	2.15	
7/18/02	2.02	
12/5/02	2.47	Ongoing measurements

Waikoloa MLR 1 Well No. 5846-01

		Remarks
1/27/93	5.50	
3/31/93	7.37	
8/5/93	7.39	
12/7/93	7.16	
3/1/94	6.94	
6/13/94	6.98	
9/7/94	7.13	
4/27/95	7.24	
12/6/95	6.79	
3/6/96	6.75	
10/1/96	6.92	
12/5/96	7.16	
3/20/97	7.04	
6/18/97	6.94	

9/10/97	7.12	
12/9/97	7.06	Pump installed.

Ouli 1 Well No. 6046-01

		Remarks
1/27/93	12.25	
12/7/93	12.16	
3/1/94	12.04	
6/13/94	12.15	
9/7/94	12.38	
4/27/95	12.30	
9/21/95	12.22	
12/6/95	11.87	
3/6/96	11.78	
6/26/96	11.68	
10/1/96	11.98	
12/5/96	12.19	
3/20/97	12.17	
6/18/97	12.05	
9/10/97	12.32	
12/9/97	12.06	
3/5/98	12.03	
6/24/98	11.89	
10/14/98	12.45	
4/27/99	12.19	
8/4/99	12.02	
12/6/99	13.16	
2/23/00	12.75	
6/6/00	12.86	
8/30/00	12.78	
1/11/01	12.83	
4/26/01	13.71	
7/26/01	12.97	
12/6/01	12.93	
7/18/02	12.76	Access becoming increasingly difficult due to locks.

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		Remarks
1/27/93	10.52	
3/31/93	11.46	
8/5/93	10.24	
12/7/93	10.35	
3/1/94	10.28	
6/13/94	10.32	
9/7/94	10.55	
4/27/95	10.52	
9/21/95	10.24	
12/6/95	10.46	
3/6/96	10.05	
6/26/96	9.89	
10/1/96	10.18	
12/5/96	10.38	
3/20/97	10.36	
6/18/97	10.24	
9/10/97	10.51	
12/9/97	10.29	

3/5/98	10.27	
6/24/98	10.03	
10/14/98	10.65	
1/26/99	10.32	
4/27/99	10.40	
8/4/99	10.23	
12/6/99	11.39	
2/23/00	10.96	
4/26/01	10.93	
7/26/01	11.17	
12/6/01	11.13	
7/18/02	10.98	Access becoming increasingly difficult due to gate lock