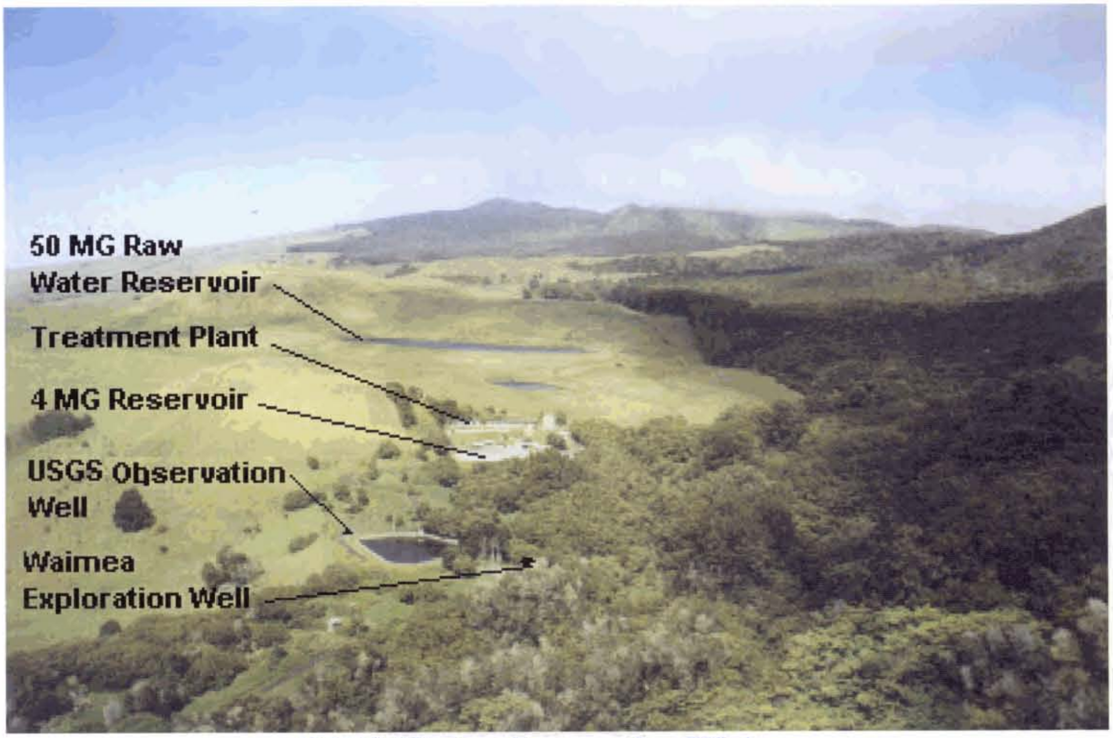
2/1/2001

Hydrogeologic Study of the Waimea High-Level Ground Water

February, 2001



DWS Water Source for Waimea

Prepared for the County of Hawaii Department of Water Supply

By Waimea Water Services, Inc.

CWRM REF ID: 2297

TABLE OF CONTENTS

List of Illustrations

Acknowledgements

We wish to thank Milton Pavao, his staff and Board for undertaking this study and for contracting Waimea Water Services, Inc. to pursue it. Special thanks go to Kae'o Duarte for his contributions and Pat Shade for the consultations and advice. Bob Acree of Kohala Ranch, Steve Hurwitz of C and H Properties, Inc., Andy Monden of DLNR, and Gordon Tribble of the USGS offered keys and access to their wells. Steve Green of the West Hawaii Water Company provided water-level records for Waikoloa Well #1. Mahalo to Jim Kauahikaua and Arnold Okumura of the Hawaiian Volcano Observatory for the many discussions and papers on geology and geophysics of Hawaii.

Executive Summary

The County of Hawaii Department of Water Supply contracted with Waimea Water Services, Inc., to conduct a hydrogeologic study of the Waimea high-level ground water. The study covered a total area of 122,023 acres from the summit of the Kohala Mountain to the 5000' elevation on the northern slope of Mauna Kea.

The purpose of the study was to evaluate the potential of the high-level aquifer system to supply the expanding village of Waimea and the availability of additional water for the leeward shoreline.

An update of geologic information is provided as well as subsurface information on the gravity anomaly contours and a slope projection indicating the southern extension of the Kohala volcanic rift zone. High-level dike and fault confined ground water is found in the rift zones of the Kohala Mountain and Mauna Kea.

Two water budget models were used to estimate the total recharge ranging from 40 to 60 mgd. Specifically, a primary recharge and development area was outlined where the highest water table elevations were found (+1600' to 1700'). Estimates of recharge in the primary area near Mud Lane range from 8.5 to 10 mgd. Additional development along Mamalahoa Highway in a westerly direction would increase the potential yield but would require more pumping lift.

It is estimated that the dike and fault confined compartments of the high-level aquifers extend to sea level and contain storage of between 2.17 and 4.8 trillion gallons. The top 50' of aquifer have a storage capacity of about 10 billion gallons as compared with the present surface water storage of 150 million gallons.

A transmission routing along the future Waimea Bypass Highway from the primary source area is recommended along with a reservoir located at Mana road with an over flow at elevation 2960'. A reservoir would also be located between the Waimea-Kohala Airport and Puu Pa at elevation 2500' with an over flow of 2521.5' to coincide with the Waiaka Tank.

Four exploration sites are recommended to better define the water-levels and gradients. Water level recordings are also needed.

Introduction

The water supply for the village of Waimea, Hawaii (Kamuela) and vicinity has traditionally come from surface-water (stream) diversions. This source was adequate when the village had only a few hundred persons, but since the 1940's, the population growth has increasingly taxed the surface-water system (see chart on page 6 for summary of water development in South Kohala).

The first efforts to improve the water supply came in the early 1940's with the sudden addition of 20,000 U. S. Marines in World War II. The Marines significantly increased surface-water diversion, built storage, added treatment and made the first attempt (dry) at drilling (Well 6239-01). In the past twenty years, the County Department of Water Supply (DWS) upgraded the water treatment facilities to meet both the increased population demands and the latest standards of the USEPA and the Safe Drinking Water Act. This upgrade continued to emphasize surface water as the source.

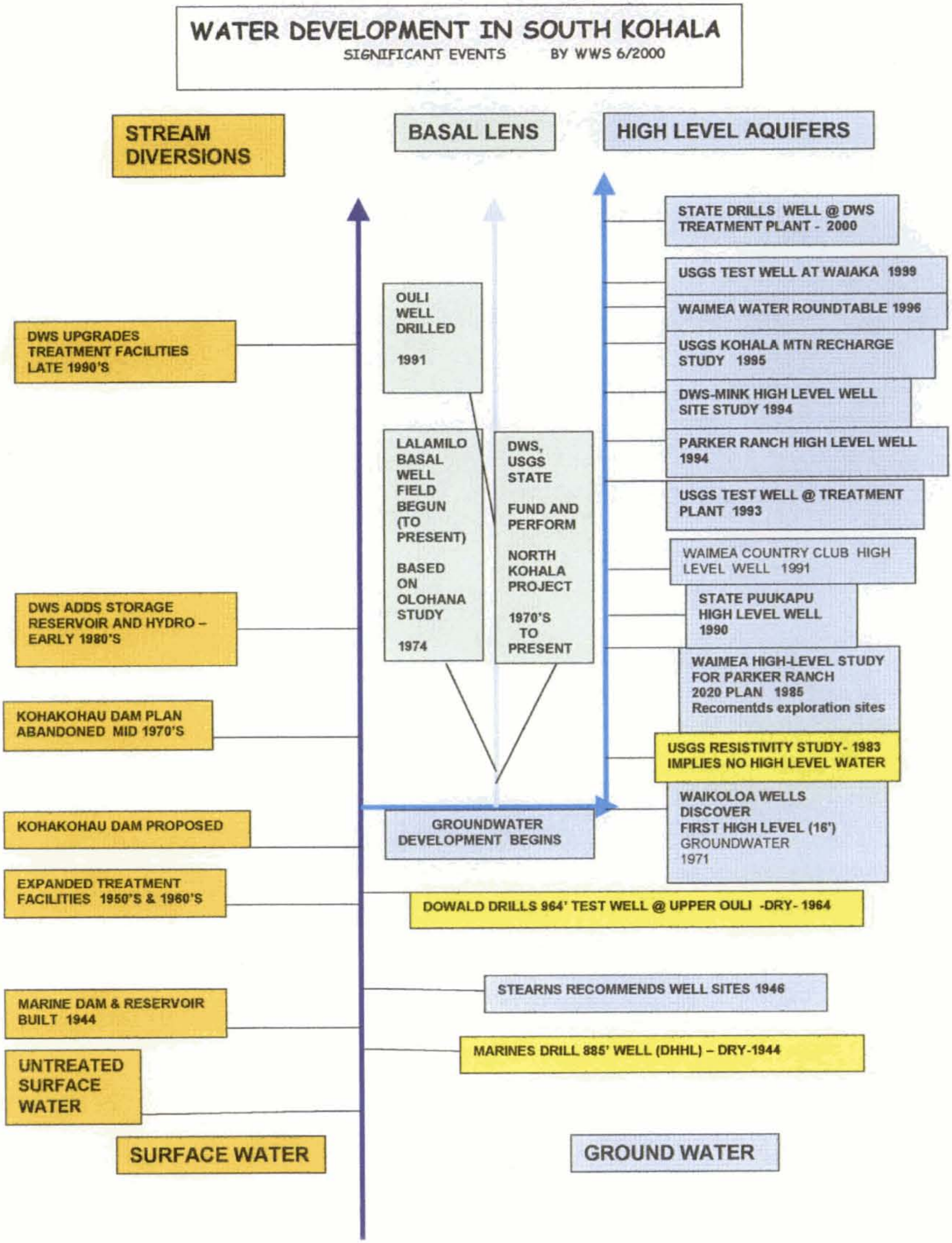
The initial assessment of the regional potential was published in 1946 (Stearns and Macdonald 1946). This study first explained the existence of high-level ground water within the Kohala Mountain. However, the first production well, Puukapu (6337-01), was not completed until 1990. Today, the Waimea Country Club Well (6235-01) is the only well in regular production.

The continued reliance on surface water to meet the increasing domestic water demand is cause for concern, especially during droughts. In the prolonged dry periods of 1961-62 and 1983, for example, the community was placed on water rationing. The DWS, on occasion, requests cut backs in normal consumption. The steady availability and reliability of high-level ground water demonstrates that the expanding water needs of South Kohala can best be met by stepping up the development of new wells.

Historically, the surface-water system of Waimea was considered appropriate because it required no pumping and was relatively inexpensive to produce. It originally delivered potable water as far west as Puako, but these deliveries ceased with development of the Lalamilo well field. Water deliveries to Paauilo, to the east, are now normally provided by a local well. Increasingly, the Waimea demand alone has begun to tax the reliability of the system, even with a raw water storage capacity of 150 million gallons.

The growing demand for additional water to serve the leeward shore prompted the DWS to evaluate the feasibility of importing water from North Kohala. However, the discovery of the high-level ground water in the Waimea area in the 1990's led the DWS to consider a more local subsurface supply.

The present study is being conducted to evaluate the potential of the Waimea high-level aquifer system as the local source of additional water to meet the growing demand for water. This study is particularly important in laying out the baseline information for future water system development.


WATER DEVELOPMENT IN SOUTH KOHALA
SIGNIFICANT EVENTS BY WWS 6/2000
STREAM DIVERSIONS
BASAL LENS
HIGH LEVEL AQUIFERS
STATE DRILLS WELL @ DWS TREATMENT PLANT - 2000
USGS TEST WELL AT WAIAKA 1999
WAIMEA WATER ROUNDTABLE 1996
USGS KOHALA MTN RECHARGE STUDY 1995
DWS-MINK HIGH LEVEL WELL SITE STUDY 1994
PARKER RANCH HIGH LEVEL WELL 1994
USGS TEST WELL @ TREATMENT PLANT 1993
WAIMEA COUNTRY CLUB HIGH LEVEL WELL 1991
STATE PUUKAPU HIGH LEVEL WELL 1990
WAIMEA HIGH-LEVEL STUDY FOR PARKER RANCH 2020 PLAN 1985 Recomentds exploration sites
USGS RESISTIVITY STUDY- 1983 IMPLIES NO HIGH LEVEL WATER
WAIKOLOA WELLS DISCOVER FIRST HIGH LEVEL (16') GROUNDWATER 1971
OULI WELL DRILLED 1991
LALAMILO BASAL WELL FIELD BEGUN (TO PRESENT) BASED ON OLOHANA STUDY 1974
DWS, USGS STATE FUND AND PERFORM NORTH KOHALA PROJECT 1970'S TO PRESENT
GROUNDWATER DEVELOPMENT BEGINS
DWS UPGRADES TREATMENT FACILITIES LATE 1990'S
DWS ADDS STORAGE RESERVOIR AND HYDRO – EARLY 1980'S
KOHAKOHAU DAM PLAN ABANDONED MID 1970'S
KOHAKOHAU DAM PROPOSED
EXPANDED TREATMENT FACILITIES 1950'S & 1960'S
DOWALD DRILLS 964' TEST WELL @ UPPER OULI -DRY- 1964
STEARNS RECOMMENDS WELL SITES 1946
MARINE DAM & RESERVOIR BUILT 1944
MARINES DRILL 885' WELL (DHHL) – DRY-1944
UNTREATED SURFACE WATER
SURFACE WATER
GROUND WATER

The original study contract covered the evaluation of about 82,566 acres, which included a portion of the Kohala Mountain up to the North/South Kohala District Boundary. The study was aimed at determining a reasonable estimate of the quantity of ground water which could be developed and where best to develop the water sources. As the first estimates of recharge to the high level aquifer were defined, however, it appeared that the original study area should be expanded to include a portion of the north slope of Mauna Kea. New geologic information gathered and reviewed at the same time indicated both the need and justification to extend the initial study area. In December of 2000, the area was increased and about 39,457 acres were added.

The Study Area

The high-level aquifer system has been known since the construction of the Lower Hamakua Ditch construction in the early 1900's. Since that time, several studies, beginning with Stearns and Macdonald in 1946, have referred to the possible development of wells. The Marine Well was drilled from an elevation of 2850' to just below 2000' and was dry. As successful wells were constructed and tested, the potential of the high-level ground water began to be better known.

The study area was selected to include all of the known or suspected high-level dike/fault confined ground water which could be developed at or below the main Department of Water Supply (DWS) service reservoir located at elevation 3000' (see cover photo). Also included were areas of the Kohala Mountain and Mauna Kea, which overlie or may contribute recharge to the high-level aquifer beneath the Waimea Plains. About 82,566 acres were originally included. Subsequently, an additional 39,547 acres were added.

A grid (shown below in blue – Figure 1) was developed to facilitate the water budget and storage calculations. The grid is based upon the known and suspected geologic features which might act to retain the ground water in a high-level aquifer system. It is likely that the dikes and faults of the Kohala Mountain and the rift zone on the north slope of Mauna Kea are the primary features.

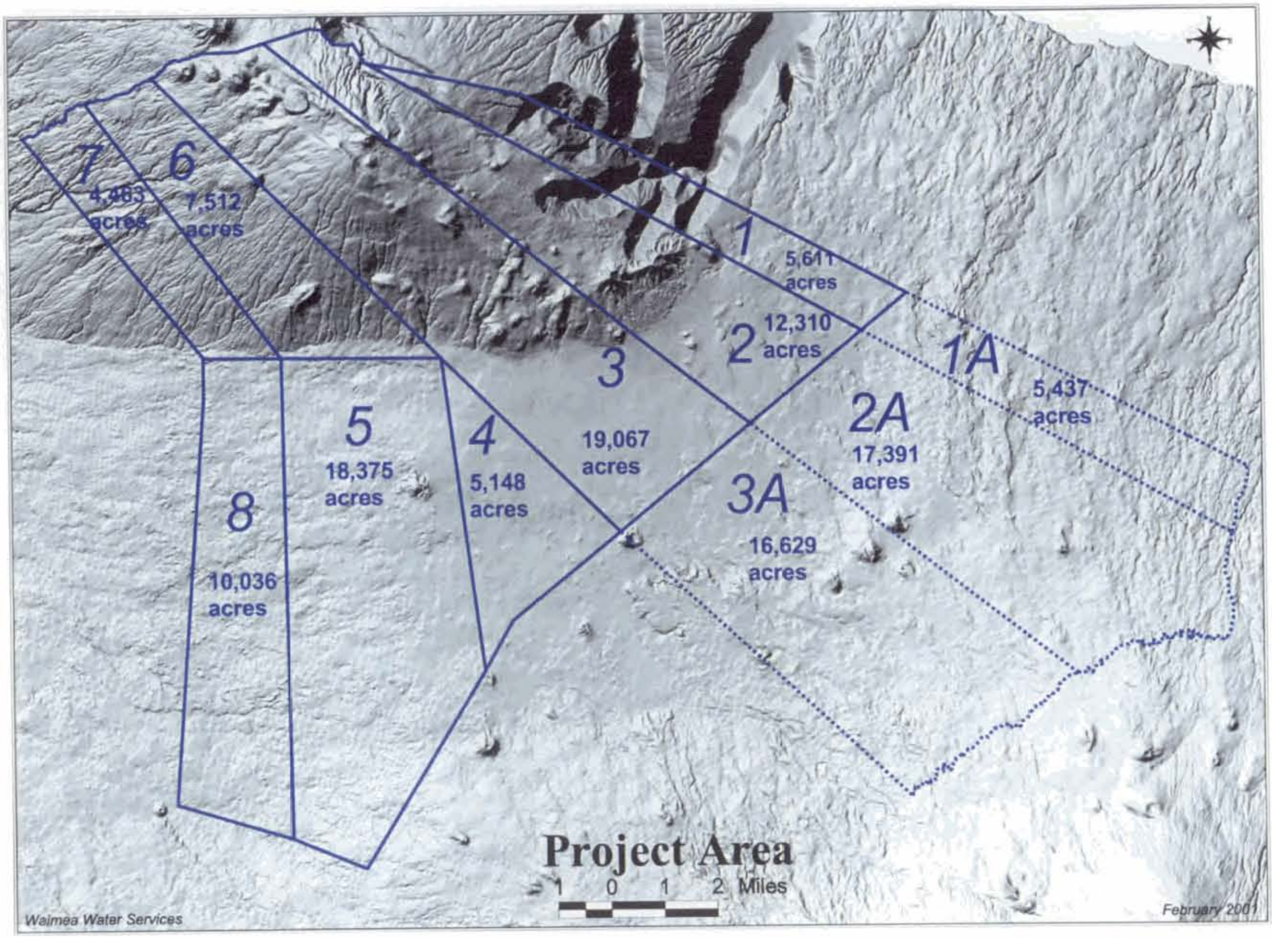
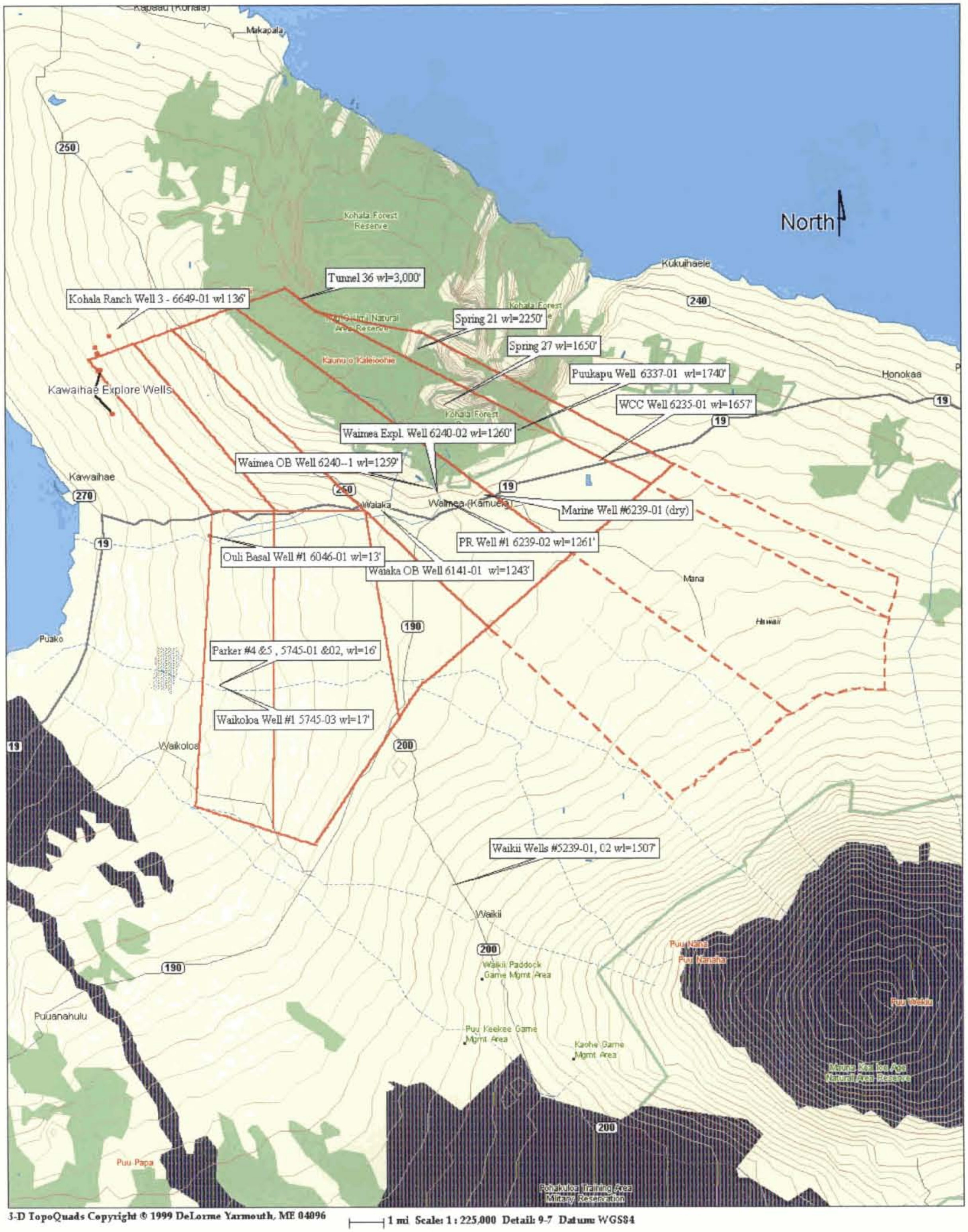


Figure 1

A well map (Figure 2) contains the location of the various wells and springs discussed in the report. In addition to the well name and state well number, a water elevation is shown.

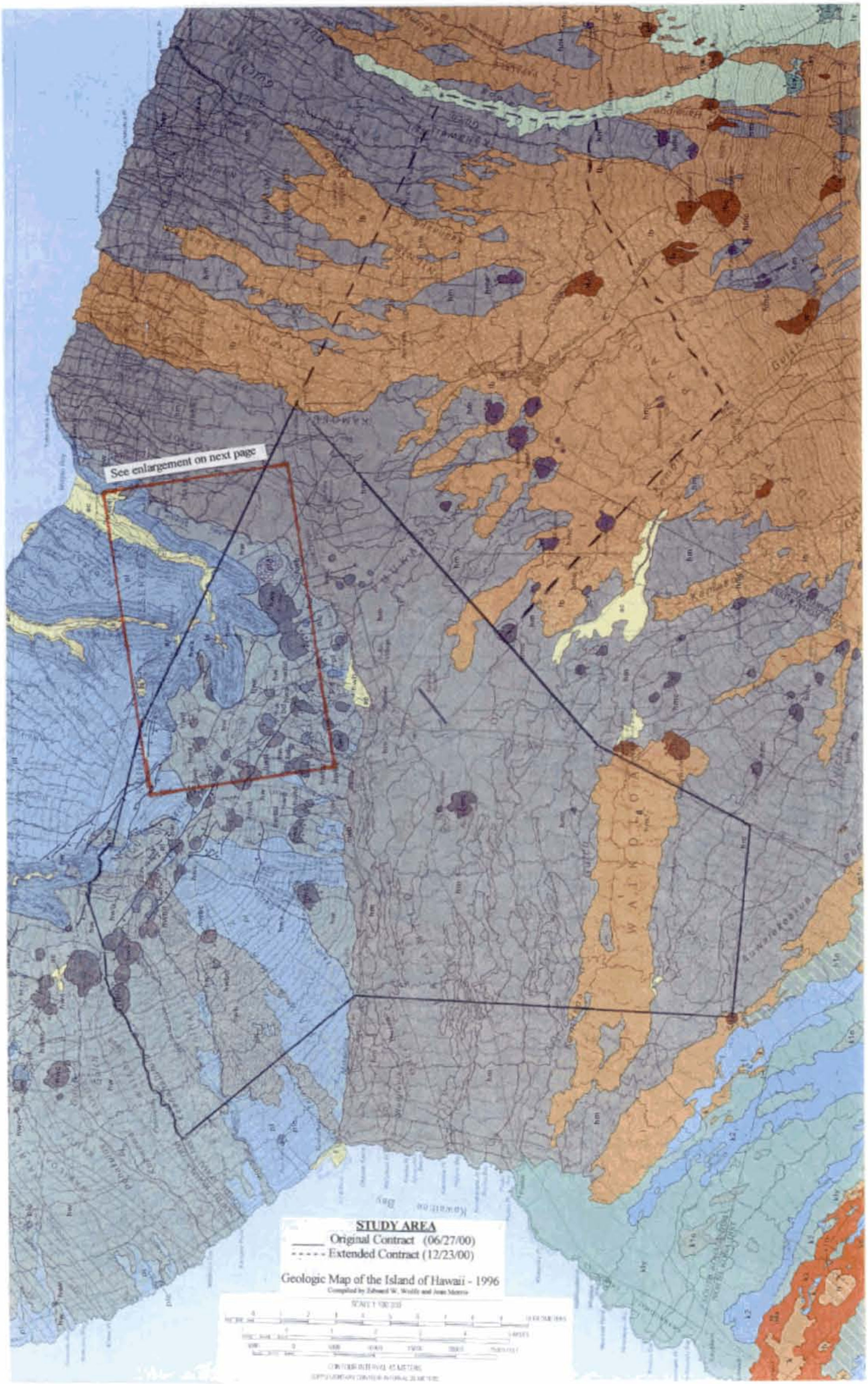


Wells and Springs Location Map - Figure 2

Geology

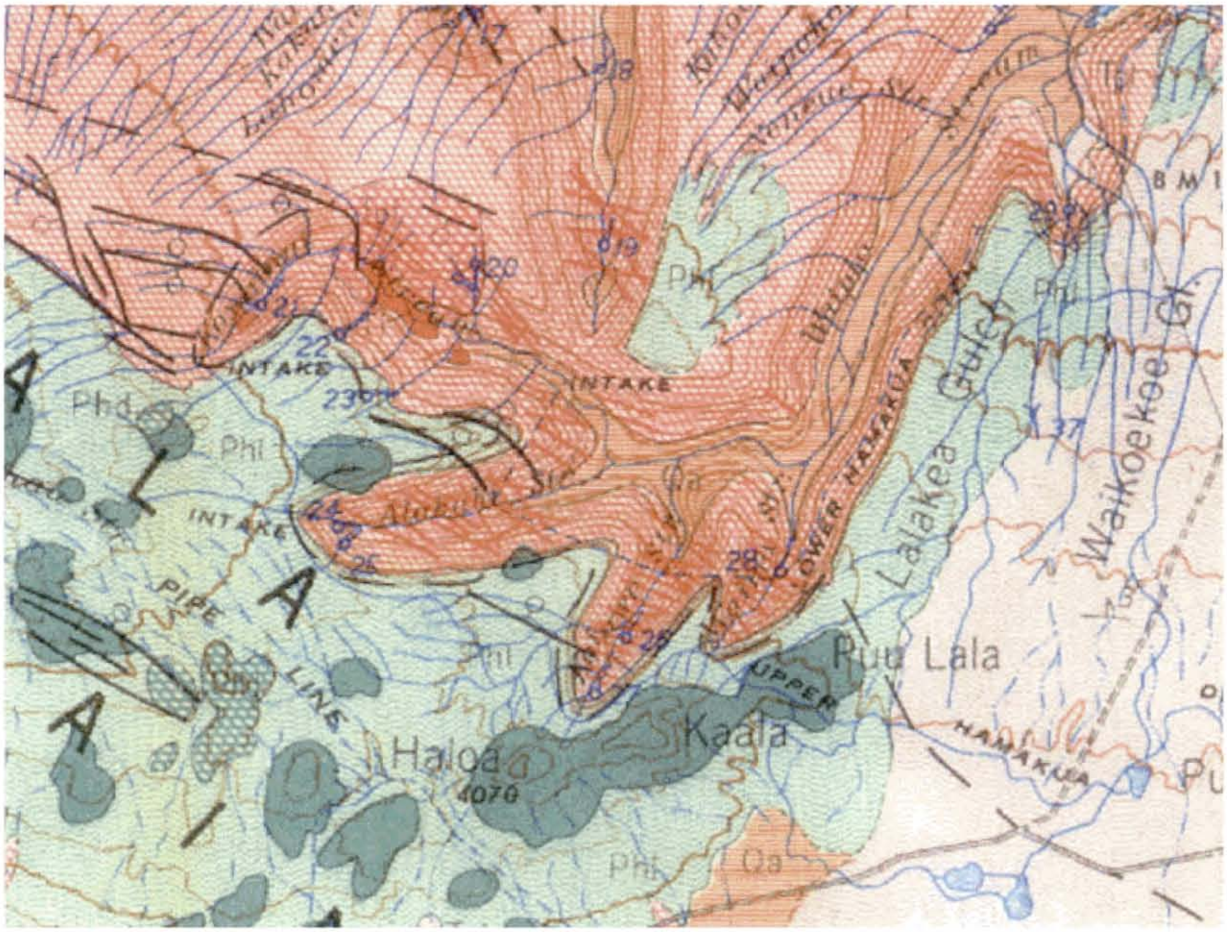
The Waimea high-level groundwater system is situated within the rift zone structures of Mauna Kea and the Kohala volcanoes. Further definition of the nature and extent of the high-level groundwater occurrence will depend on obtaining a better understanding of the structural geology. The aerial geology of the island of Hawaii has been studied extensively and is presented in the 1996 map of the US Geological Survey. The high-level study area is outlined in the portion of the geologic map in Figure 3.

The age of the older Kohala volcanics is dated at 700 thousand years before present (bp) and the youngest at 120,000 years bp. The oldest mapped age of the Mauna Kea flows is 250,000 years bp and the youngest is dated at 14,000 years bp.



Geologic Map High Level Study Area - Figure 3

As the younger Mauna Kea volcano emerged, there must have been some inter-fingering with younger lavas of the Kohala volcano beneath the plains of Waimea. Drilling data obtained from the water wells along the northern edge of the Waimea plain also indicate that the youngest Mauna Kea flows overlie the weathered surface of the Kohala volcano. The Kohala volcano is represented in the Geologic Map (Figure 3) by the blue and blue gray coding with the letter hw for the Hawi volcanics and pf for the Pololu volcanics. The Mauna Kea coding is gray (hm) and burnt orange (l).



Waipio Tributaries

Key:
Dikes (red bars)
Faults (solid and dashed bars)
Springs (circles with tails)

Scale (in feet):
10,000 — 0

From Stearns and MacDonald 1946

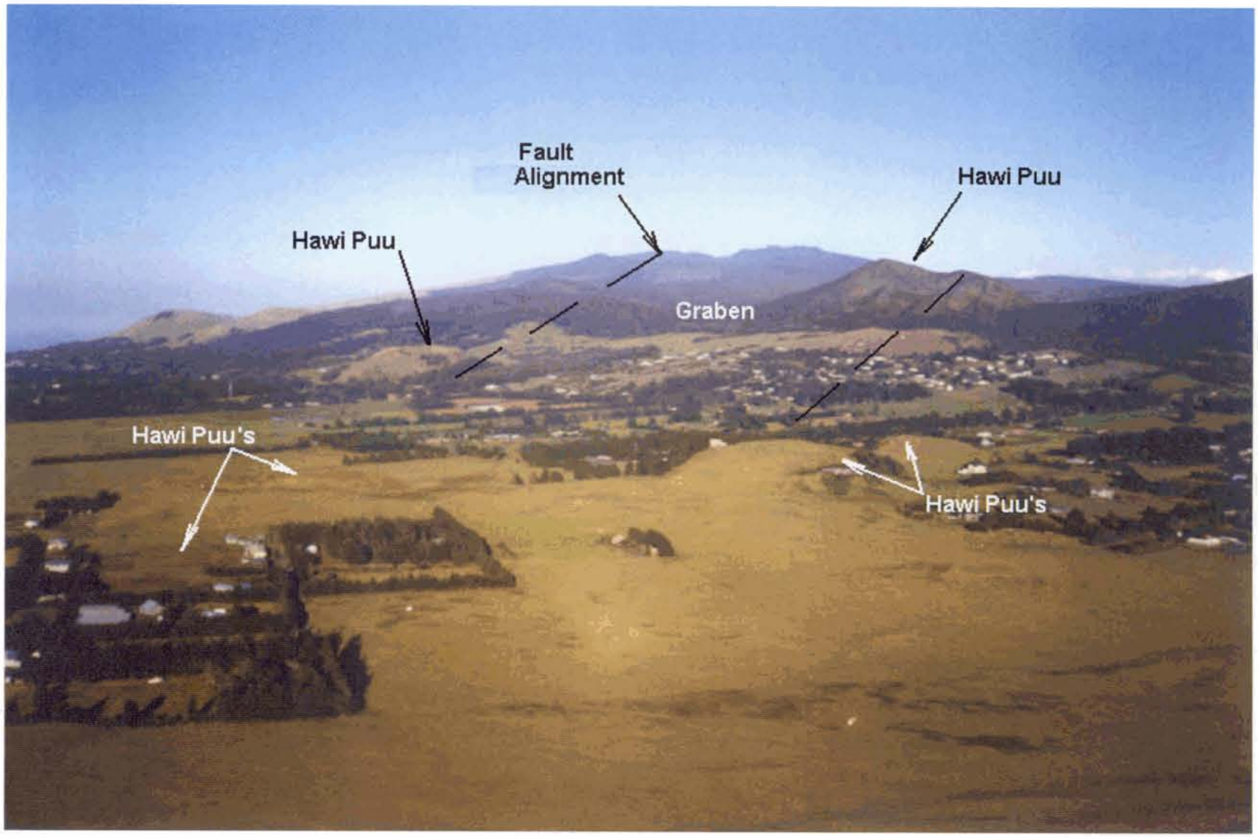
Figure 4

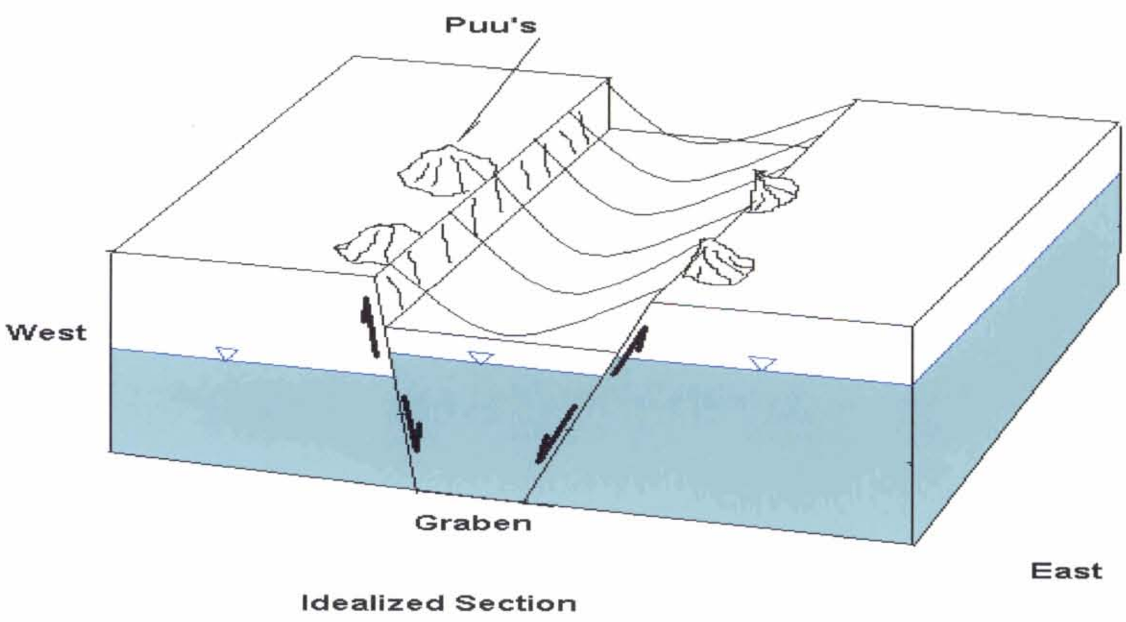
As indicated on the geologic map, there are numerous pyroclastic (ash, cinders and bombs) vents (puu) on the northern flank of Mauna Kea. These vents are associated with the feeder dikes which, when intersecting each other, have created structural enclosures suitable for containing ground water above sea level.

The windward Kohala volcano has been extensively described by Stearns and Macdonald (1946), and many structures within the mountain have been exposed in the eroded valleys (Figure 4). The extensive array of dikes and faults in the windward valleys support a number of high-level springs (see Well Map, Figure 2). The Lower Hamakua ditch intersects many dike compartments that supply water to the ditch.

The higher water levels of the wells on the east side of Waimea (1600' to 1700'), versus in the Parker Ranch Well (1261'), indicates that the water table drops nearly 400' in 4 miles across the Kohala Mountain rift zone.

A 1985 study by Bowles and Nance speculated on the significance of a major graben (down throw fault block) structure trending parallel to the rift zone of the Kohala volcano. A number of the younger eruptions of the Hawi volcanics occur along each edge of the graben. The water level drop from east to west appears to be a result of compartments or boundaries within such a structure. The graben appears to extend beneath the Mauna Kea surface lavas, as evidenced by several vents of the Kohala volcano-Hawi series, which are located along Mana road. These puu consist primarily of pyroclastic materials and their location clearly indicates the subsurface extension of the Kohala volcano.

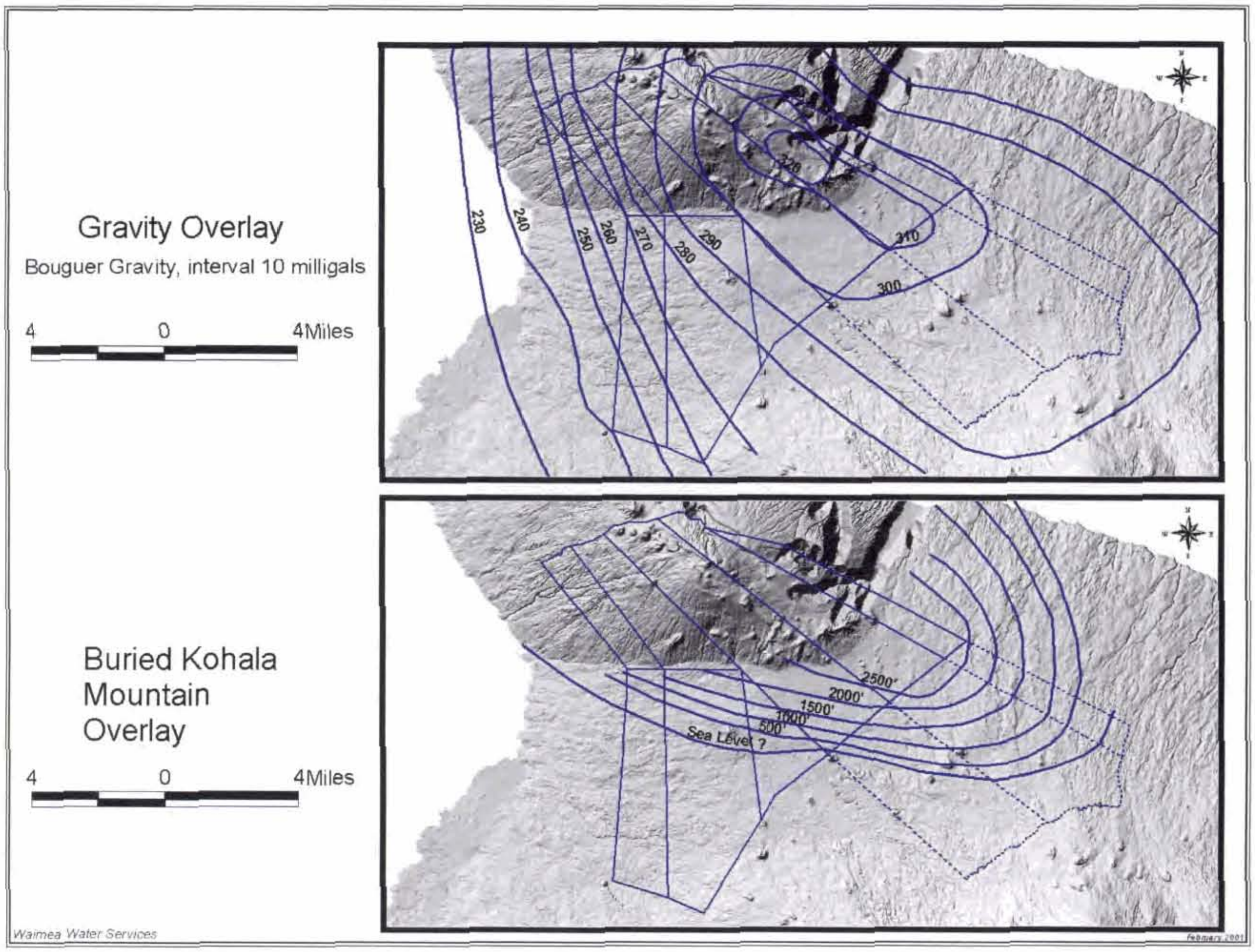




Graben – Figure 5

Certain geophysical tools have also been used in the area, with the gravity surveys providing the best structural clues to date. Early mapping of gravity density anomalies, by Kinoshita (1965), showed the gravity high of the Kohala Mountain extending beneath the Mauna Kea flows. More recently (October 2000), Kauahikaua, et al., have projected the southeasterly trend of the Kohala rift to the offshore Hilo Ridge.

A computer slope projection of the Kohala volcano was prepared by Waimea Water Services, Inc., from the USGS topographical map base. This projection was used as the basis for drilling the Waimea Country Club Well (6235-01) in 1991, which discovered a high-level water table standing at elevation 1657'. Figure 6 shows the relationship of the gravity anomaly and the slope projection. The association to the rift zone of the Kohala volcano is quite evident.



Kohala Mountain Gravity/Subsurface Overlays - Figure 6

In addition, the recent discovery (Holcomb, et al. 2000) of Kohala lavas at the base of the Hilo Ridge and the gravity data presented by Kauahikaua supports a hypothesis that the rift zone and, thus, the high-level aquifer system may extend into the rainy region above Ahualoa on the windward slope of Mauna Kea.

Moore, et al. 1989, presented conclusive evidence of a major slump and submarine avalanche associated with the deep windward valleys of the Kohala volcano. There can be no doubt that the faulting associated with the slump extends to the leeward slopes and is most probably responsible for the extensive graben discussed by Bowles and Nance (1985). How faults relate to high-level ground water has yet to be adequately explained. There is evidence elsewhere on Hawaii, namely in the Kona Districts, that faulting has a major influence in retaining ground water at significant elevations above sea level. The intrusion of dikes throughout the rift zone of the Kohala Mountain as well as the north slope of Mauna Kea appears to be the primary structures retaining the high-level groundwater reservoirs.

Water Budget

Understanding of the Waimea high-level aquifer system is presently limited and the orderly development of these water resources will depend on a growing knowledge of the sustainability of the aquifer system. The State of Hawaii Commission on Water Resource Management (CWRM) uses the hydrologic term "sustainable yield" to describe the suggested limit of water which should be developed from a particular aquifer. The sustainable yield of the high-level aquifer is based on groundwater recharge estimates.

A water budget is a common method used to estimate the long-term reliability of an aquifer. In the case of the Waimea high-level aquifer, the estimates of recharge indicate the first approximation of developable limits. In its published estimates of sustainable yield, the CWRM (1990) has divided the island aquifer sectors into systems, which are primarily based on watersheds or other geographic features. The water budget calculated for this study is for areas defined by geologic structures and the most likely area for water development.

Ground water is replenished by the infiltration of rainfall that percolates through the root zone in the soil to bedrock. Groundwater recharge can be estimated by a water accounting model similar to that developed by Thornthwaite (1948) and Thornthwaite and Mather (1955) that balances input of rainfall and fog drip with output of runoff, evapotranspiration, groundwater recharge, and the change in soil-moisture storage expressed by:

Eq 1. $G = P + F - R - ET - \Delta SS$

Where:
G = groundwater recharge,
F = fog drip,
P = rainfall,
R = direct runoff,
ET = evapotranspiration, and
ΔSS = change in soil-moisture storage.

Direct runoff and fog drip are calculated separately as a percentage of rainfall. Thus, the model calculates groundwater recharge, evapotranspiration and the change in soil-moisture storage. Daily, hourly or smaller time intervals of climatologic and soil-water data collected from a dense network of gages over a small aerial extent can more accurately determine volumes of water in each water-budget component. However, these data are not available in the project area and therefore, a monthly budget was calculated. A monthly water budget is a coarse representation of the allocation of water in the hydrologic cycle. This model does not simulate the extremes of nature. For example, the influence on the water balance from a slug of runoff and groundwater recharge generated from an intense 2-day storm will be moderated by the monthly accounting. By using mean monthly data, the budget calculates average component volumes useful for regional assessments of resource availability.

Kamakoa Stream – Flood Event of November 2, 2000 – Figure 7

Rainfall

The rainfall distribution in the project area is influenced by the orographic effect of both Mauna Kea and the Kohala Mountain. The small part of the project area that is windward of the Kohala Mountain receives abundant rainfall, from about 80 to nearly 150 inches per year. In the lee of the Kohala Mountain crest, rainfall decreases dramatically to about 10 inches per year near the west coast. It is considerably drier in the extended project area through the saddle between the two mountains where rainfall ranges from about 14 inches in the west to a small area in the east that receives about 70 inches per year.

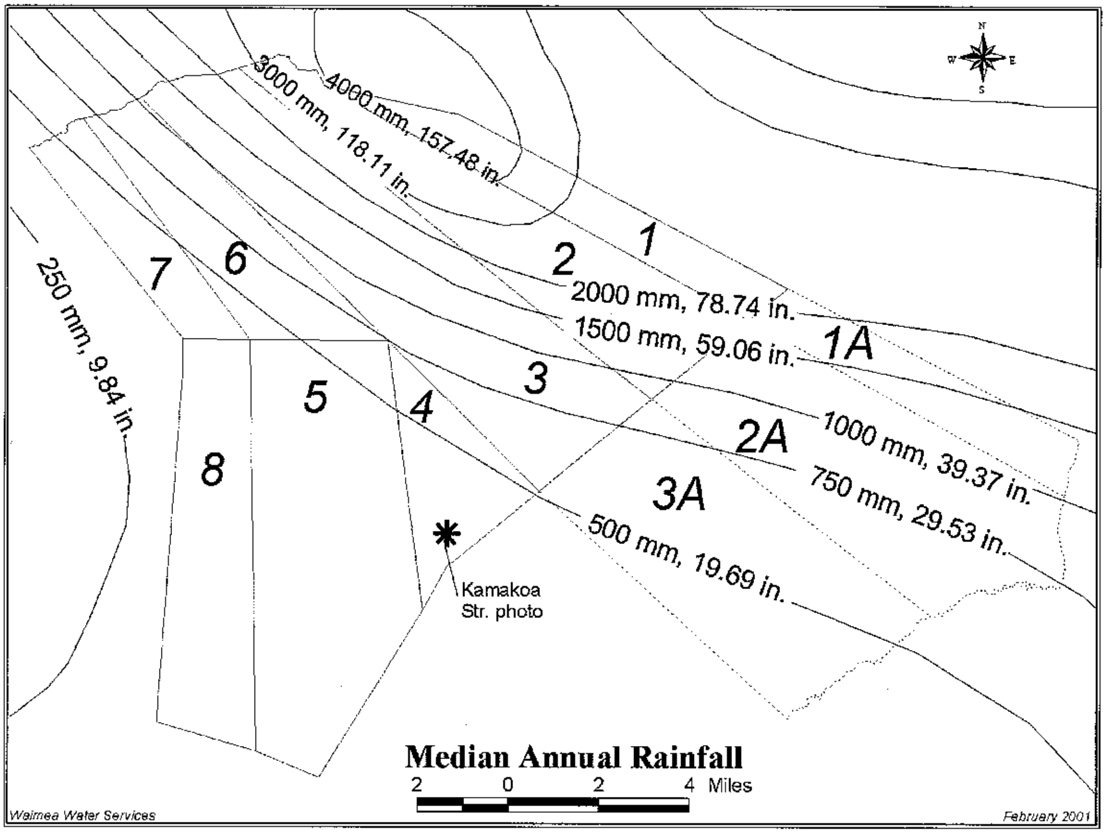


Figure 8

The twelve monthly median rainfall maps (Giambelluca and others, 1986) were digitized for the use in the GIS model. The rainfall value applied to the area between the isohyets is the average value of the two bounding isohyets.

Fog

Upslope fog in Hawaii occurs predominantly by the cooling to the saturation point of warm moist marine air as it moves upslope. The water yield of fog is a function of droplet size, which tends to be large in marine air masses (McKnight and Juvik, 1975). Different studies have found that the most productive fog occurs in non-raining cloud decks formed in degenerating marine air masses, a situation that occurs frequently in the project area (Grunow, 1960 and McKnight and Juvik, 1975). The depth of the inland cloud structure on the upper slopes at 1800 meters (5905 feet) is decreased from that at sea level due to the compression of ascending air between the mountain and the trade wind inversion. This shallow cloud formation limits the growth of droplets to a size optimal for forest interception (McKnight and Juvik, 1975). Ekern's work on Lanaihale found fog interception equal to 2/3 of rainfall measured in the area. On exposed windward Mauna Loa, Juvik and Nullet (1995) developed a general model to predict fog interception relative to rainfall as a function of elevation on windward slopes between about 3950 and 5900 feet. Juvik and Ekern (1978) describe a well-defined fog belt on windward Mauna Loa between 1500-2500 (4920-8200 feet) meters with fog amounts up to one-half the rainfall, about 750 mm (29.55 inches). On leeward Mauna Loa, fog increases with elevation up to about 2000 meters (6560 feet), with fog equal to one-quarter of rainfall, or about 250 mm (9.85 inches). Juvik and Nullet's model was used to estimate the contribution of fog to the water budget in the project area. At 1500 meters (4920 feet), this model indicates the fog contribution is from 20 to 80 percent of rainfall through the months. Casual observations in the project area indicate the fog zone may extend lower to about 3000 ft. Further investigations to measure fog drip at lower elevations within the project area are necessary to better define this component of the water budget. Because this component is poorly known, the water budget was calculated with and without a fog component.

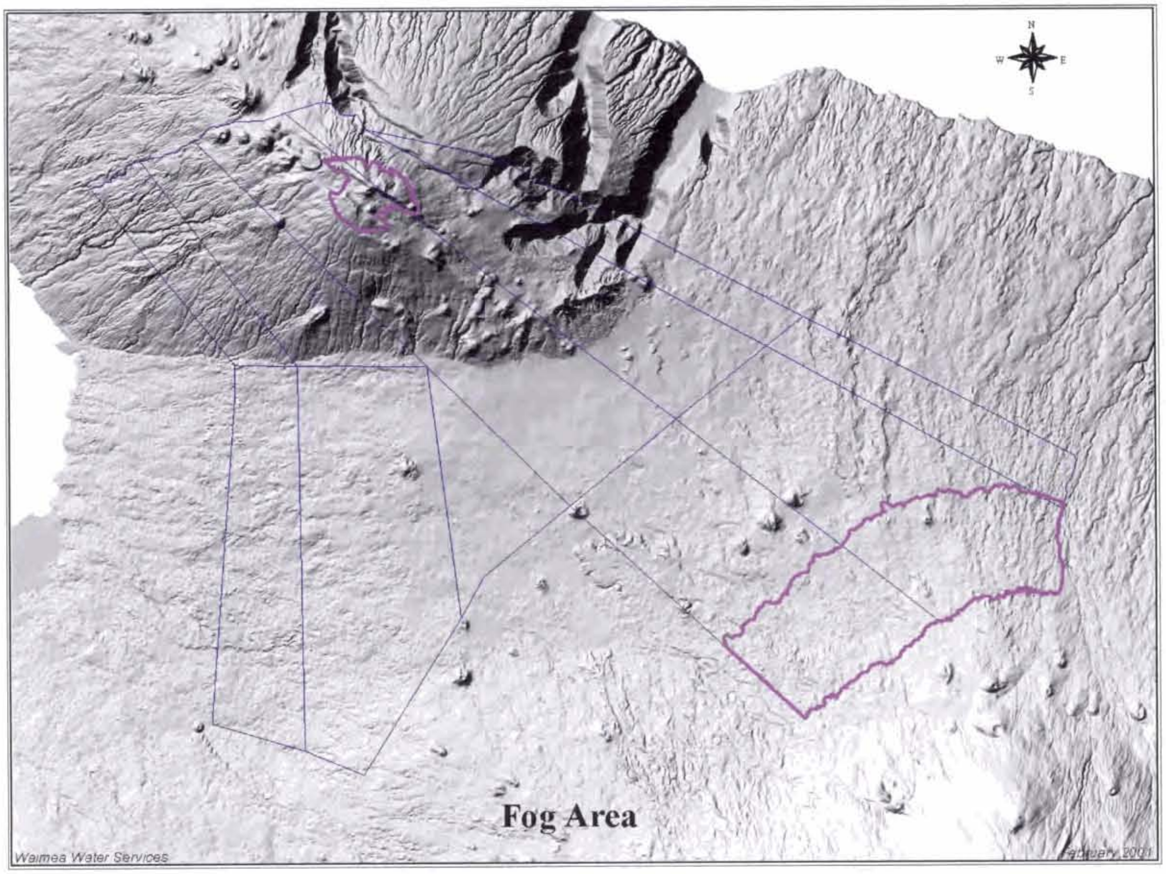


Figure 9

Direct Runoff

Direct runoff, the stream flow generated quickly from rainfall, is calculated as a percentage of rainfall in the water-budget model. In most of the project area there are no long-term continuous stream flow data, particularly for intermittent streams. Because streams that originate on the leeward side of the Kohala Mountain crest rarely flow to the ocean, minimal runoff-rainfall ratios were estimated at 0% to 5%. These low ratios reflect that most runoff generated within this leeward area infiltrates before it leaves the project area as runoff into the ocean. In the high rainfall area windward of the Kohala Mountain crest, monthly runoff-rainfall ratios were calculated for the Alakahi basin from 36 years (1948-1983) of rainfall data at Station 190 (state key number) and 34 years (1964-1997) of stream flow data at USGS Station 16725000. A flow-separation program (Wahl and

Wahl, 1995) was used to eliminate the slow drainage from bank storage and the groundwater discharge component, or base flow, from these stream flow data. The resulting direct runoff-rainfall ratios were applied in the windward part of the project area. Direct runoff-rainfall ratios were calculated after base flow separation, for Kohakohau drainage basin, delineated at the original location of USGS Station 16756000, from 10 years (1956-1965) of daily stream flow data and median monthly rainfall data.

Evapotranspiration

Evapotranspiration (ET) is the quantity of water evaporated from water and soil surfaces and transpired by plants. ET can be measured by evaporimeters or lysimeters, or calculated mathematically from various climatic data, none of which are available in the project area. However, ET can be estimated from soil and pan evaporation data.

Soil Characteristics

Soils in the project area have been mapped and digitized by the Natural Resources Conservation Service (Sato and others, 1973). Soil characteristics are tabulated in this report (Table 1 on page 21). Available water is a measure of the quantity of water in the soil between field capacity and the wilting point; the amount of water available for uptake by plant roots. The available water value for each soil type shown in Table 1 is the average of the range of values reported in Sato and others (1973). The root depth is the depth to rock as reported in Sato and others (1973). The maximum soil storage value is the product of the root depth and the available water capacity for each soil type. Because the root depth is poorly known, the values for maximum soil storage are similarly coarse estimates. The maximum soil storage values are critical in the water-budget accounting, because they establish the limit for each soil type, above which groundwater recharge can occur. This is a weak element in the model, and frequently is the reason for what may appear to be anomalous areas on the recharge distribution maps. Currently, the Natural Resources Conservation Service is re-mapping the soils on the island; however, this information is not yet available. Adjustments to the water-budget may be necessary with the availability of new soil and data.

Table 1. Soil characteristics

Soil type	Available-water capacity (Inch per inch of soil)	Root depth (Inches)	Maximum soil-moisture storage (inches)	Permeability (inches/hour)
AIC	0.34	27	9.18	2.0 – 6.0
HCD	0.13	60	7.8	2.0 – 20.0
HDD	0.13	60	7.8	2.0 – 6.0
HTD	0.13	60	7.8	6.0 – 20.0
KCD	0.13	36	4.68	0.06 – 6.0
KfA	0.08	40	3.20	2.0 – 6.0
KGC	0.09	29	2.61	6.0 – 20.0
KNC	0.14	24	3.36	0.6 – 2.0
KXC	0.08	50	4.00	2.0 – 6.0
KYC	0.04	60	2.40	0.02 – 6.0
KZD	0.08	42	3.36	6.0 – 20.0
MaA	0.15	40	6.00	2.0 – 6.0
MLD	0.15	40	6.00	2.0 – 6.0
PLC	0.15	48	7.20	2.0 – 6.0
PRD	0.15	60	9.00	2.0 – 6.0
PVD	0.13	40	5.20	2.0 – 6.0
rAM	0.18	20	3.60	0.01 – 6.0
RB	0.15	25	3.75	2.0 – 20.0
rCL	0.01	36	0.54	6.0 – 20.0
rVS	0.02	10	0.20	6.0 – 20.0
UMD	0.15	60	9.00	2.0 – 6.0
USD	0.15	60	9.00	2.0 – 6.0
WLC	0.11	39	4.29	0.6 – 6.0
WMC	0.15	42	6.30	2.0 – 6.0
WSD	0.15	42	6.30	2.0 – 6.0

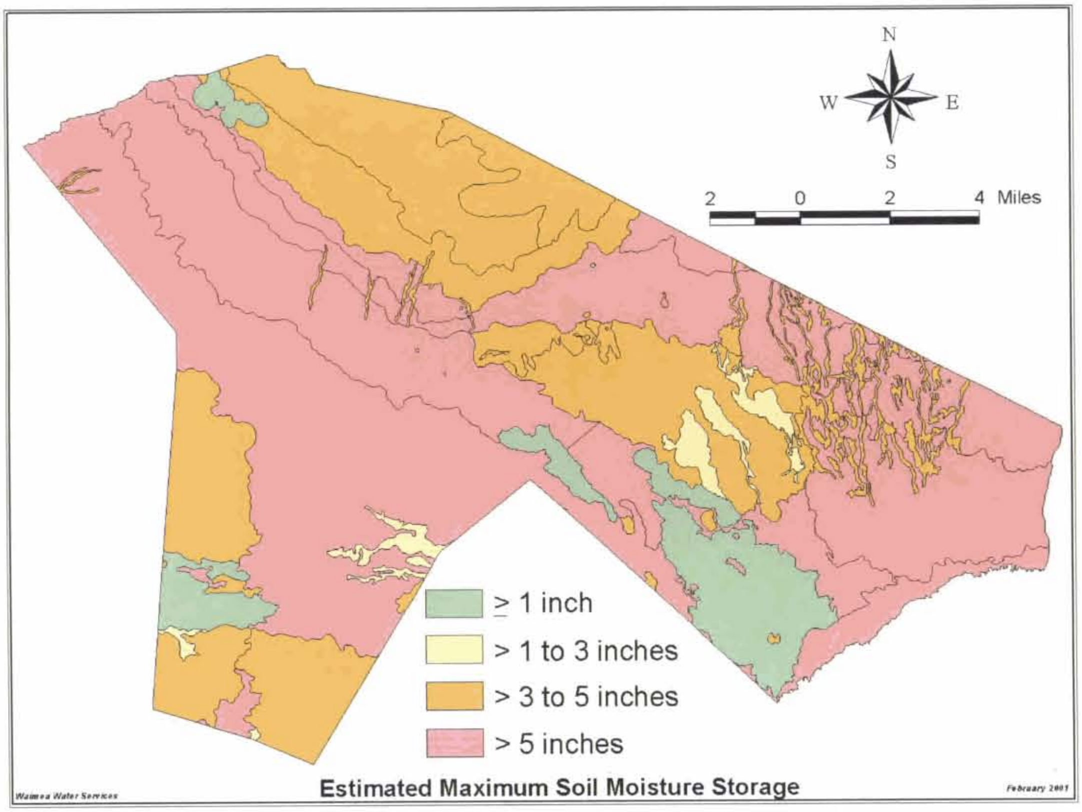


Figure 10

Pan Evaporation and Potential Evapotranspiration

A short record of pan evaporation data is available, collected at the Lalamilo agriculture station in Waimea. These data provide an estimate of the potential or maximum evapotranspiration in the area near the station. In dry areas, ET generally occurs at less than the maximum, potential rate because, without irrigation, there is a lack of water to satisfy this maximum demand. For this project it is assumed that pan evaporation equals potential evapotranspiration, a pan coefficient of 1.0, on the basis of research done in sugarcane fields in Hawaii and by Giambelluca (1983) for forests in dry and moderately wet areas. This coefficient may be as high as 1.3 in wet, forested areas (Giambelluca, 1983), and thus, ET may be underestimated in those parts of the project area.

Ekern and Chang (1985) created a map of the mean annual pan evaporation for the island of Hawaii that was digitized for the GIS water-budget model. The value assigned for the area between the lines of equal pan evaporation is the average value of the two bounding lines. Monthly pan evaporation values were calculated from each month's mean monthly to mean annual ratio, at the Lalamilo station, applied to the mean annual distribution.

Evapotranspiration and Soil-Moisture Accounting

On a monthly interval, the water-budget model calculates evapotranspiration on the basis of potential evapotranspiration, the current value of soil-moisture storage and the maximum soil-moisture storage value. In any month and for any soil type, the amount of water in soil storage cannot exceed the maximum soil-moisture storage value listed in Table 1. Evapotranspiration is also limited by the quantity of water in soil-moisture storage and cannot exceed the potential evapotranspiration value. In any month, the potential evapotranspiration value may exceed the quantity of water held in soil-moisture storage to meet that demand. Thus, evapotranspiration would occur at less than the potential evapotranspiration rate. It is also possible, in some locations and in some months that the potential evapotranspiration value is greater than the maximum soil-moisture storage value, and therefore evapotranspiration could not occur at the maximum rate. Thus, the maximum soil-moisture storage value is also an important limiting factor in the model calculation of evapotranspiration.

Because the volume of water in soil-moisture storage changes from month to month, the values for beginning soil-moisture storage in January were established objectively by running the water-budget model three times. Starting in January with maximum soil-moisture storage volumes, half of the maximum soil-moisture storage volumes, and with zero soil-moisture storage, all yielded identical ending soil-moisture storage volumes in December. These ending volumes in December were input for beginning soil-moisture storage volumes in January for the final water-budget model simulation.

Water-Budget Model Accounting

Two accounting methods were used in the water-budget model. Method I allocates excess soil-moisture to groundwater recharge first, and Method II allocates excess soil-moisture to evapotranspiration first. Method II is the standard sequence in monthly water budgeting. However, this sequence is not supported by soil infiltration rates, represented by permeability values in Table 1 (on page 21), evapotranspiration and rainfall rates in the project area. That is, in dry areas, the majority of rainfall occurs in intense events, and infiltration rates are such that water passes beyond the root depth during the period when evapotranspiration is suppressed, thus recharging groundwater. Averaging the results of the two methods attempts to mitigate the errors associated with each method.

Method I

This sequence maximizes groundwater recharge and is shown in Equations 2 through 4. The runoff for the month is subtracted from the sum of beginning soil-moisture volume and rainfall. (Fog drip would also be added to this sum for that budget scenario, but is not shown in Equation 2.) The resulting volume is the first interim soil-moisture storage value (Eq. 2). If this volume exceeds SS_{max}, the excess recharges ground water, and a second interim soil-moisture volume is calculated (Eq. 3). Evapotranspiration is subtracted from the second interim soil-moisture volume at either the maximum ET volume or at the interim soil-moisture volume, whichever is less (Eq. 4). Any water remaining in soil-moisture storage is carried over to the next month.

Eq. 2 $$X_1 = P_m - R_m + SS_m$$

X_1 = first interim soil-moisture storage volume
P_m = rainfall for the month
R_m = runoff for the month
SS_m = beginning soil-moisture storage volume for the month

Eq. 3 If $X_1 > SS_{max}$, then $X_1 - SS_{max} = G_m$ and $X_2 = SS_{max}$ OR If $X_1 \leq SS_{max}$ then $G_m = 0$ and $X_2 = X_1$

SS_{max} = maximum soil-moisture storage
G_m = groundwater recharge for the month
X_2 = second interim soil-moisture storage in the month

Eq. 4 If $X_2 \geq PE_m$ then $ET_m = PE_m$ and $X_{end} = X_2 - PE_m$ OR If $X_2 < PE$ then $ET_m = X_2$ and $X_{end} = 0$

ET_m = evapotranspiration for the month
PE_m = potential (maximum) evapotranspiration for the month
X_{end} = soil-moisture storage volume at the end of the month which becomes the beginning soil-moisture storage volume for the next month

Method II

This method maximizes evapotranspiration and is shown in Equations 5 through 7. The *runoff for the month is subtracted from the sum of the beginning soil-moisture volume,* and rainfall. The resulting volume is the first interim soil-moisture storage value (Eq. 5). If this volume exceeds potential (maximum) evapotranspiration, then evapotranspiration occurs at the maximum rate, and the second interim soil-moisture storage volume is calculated by subtracting the potential evapotranspiration volume from the first interim soil-moisture storage volume. If the second interim soil-moisture storage volume exceeds SS_{max}, then the excess recharges ground water. Any water remaining in soil-moisture storage is carried over to the next month.

Eq. 5 $$X_1 = P_m - R_m + SS_m$$

X_1 = first interim soil-moisture storage volume
P_m = rainfall for the month
R_m = runoff for the month
SS_m = beginning soil-moisture storage volume for the month

Eq. 6	If $X_1 \geq PE_m$ Then $ET_m = PE_m$ And $X_2 = X_1 - PE_m$	OR	If $X_1 < PE_m$ then $ET_m = X_1$ and $X_2 = 0$
Eq. 7	If $X_2 \geq SS_{max}$ Then $G_m = X_2 - SS_{max}$ And $X_{end} = SS_{max}$	OR	If $X_2 < SS_{max}$ $G_m = 0$ and $X_{end} = X_2$

Water-Budget Results

For this regional water-budget, the results can best be evaluated by determining the apportioning of the moisture inputs of rainfall and fog to runoff, evapotranspiration and groundwater recharge. For the budget without fog, in the original project area, runoff, evapotranspiration and groundwater recharge were 19% (40 mgd), 65% (136 mgd), and 15.6% (33 mgd) of rainfall respectively. Because much of the runoff generated within the project area does not leave the area as runoff to the ocean, a value of 19% appears reasonable. Given the diversity in the area of rainfall of greater than150 inches to about 10 inches annually, the evapotranspiration of nearly 2/3 of the total rainfall is reasonable. In the large dry area where potential evapotranspiration is quite high, there is not enough water to satisfy this demand. On the other hand, in the proportionately much smaller wet part of the project area, evapotranspiration is suppressed, although there is plenty of water to satisfy the minimal demand. Because of the opposing interaction in the model between the calculation of evapotranspiration and groundwater recharge, the 15% recharge proportion does not appear excessive as it can best be judged by the reasonableness of the evapotranspiration value.

The addition of fog in the project area only slightly changed the balance. The fog component contributed additional moisture equal to 11.5% (24 mgd) of rainfall, a fairly conservative fog estimate compared with published studies. In this water budget, the runoff, evapotranspiration and groundwater recharge proportions of rainfall plus fog are 17% (40 mgd), 60% (140 mgd) and 23% (53 mgd), respectively. These results imply the importance of a fog component in the water budget, as it increased groundwater recharge by about 7.5%. Because the fog component is poorly known, the increased groundwater recharge estimate should be viewed cautiously.

In the extended project area, a larger proportion is dry by comparison with the original project area, receiving from about 20 to 70 inches of rain annually. The water budget results are reasonable given this condition, with runoff, evapotranspiration, and groundwater recharge being 3% (2 mgd), 88% (61 mgd) and 9% (6 mgd) of rainfall, respectively. Applying fog to this area at about 10% of rainfall, did not change the above proportions of the water-budget components but, the runoff, evapotranspiration and groundwater recharge values increased to 3 mgd, 67 mgd, and 7 mgd respectively.

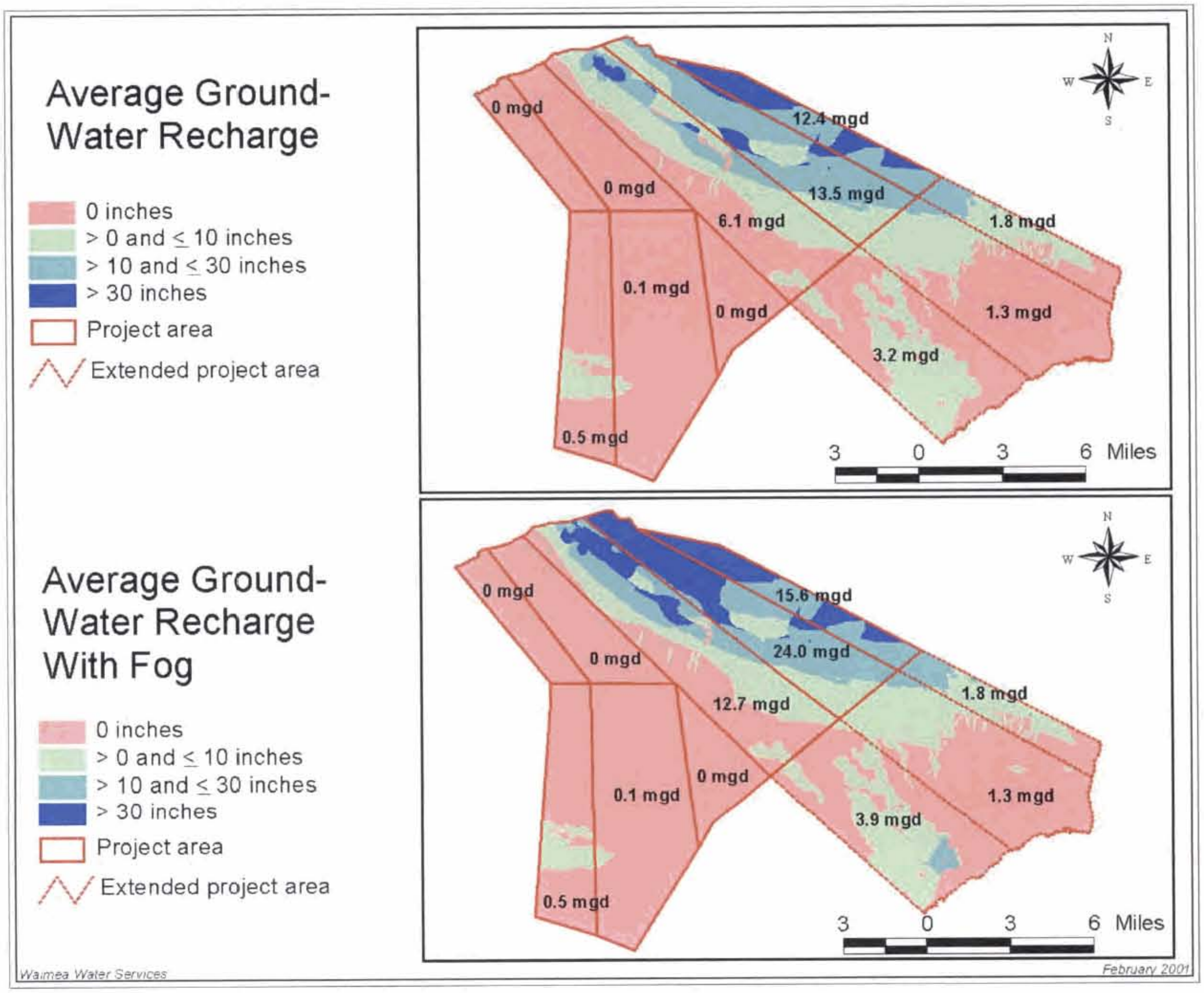
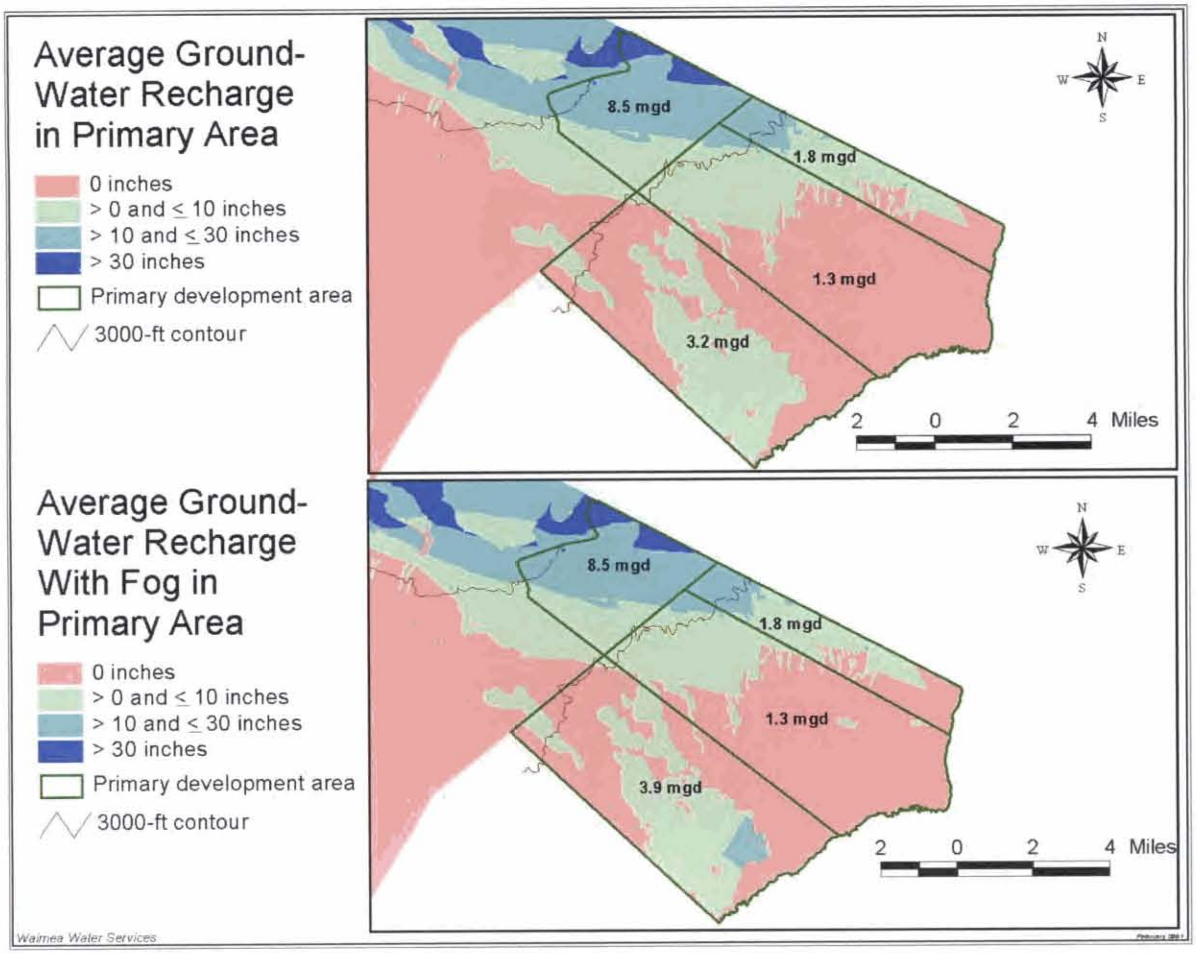


Figure 11

The primary groundwater development area consists of the extended project area and the southeast part of units 1 and 2. Within this area, groundwater recharge is estimated to be 14.8 mgd without a fog component and 15.5 mgd with a fog component.



Primary Development Area – Figure 12

The groundwater recharge distributions shown generally follow the rainfall distribution with high values occurring in the northeast part of the project area and decreasing to the west toward the coast where rainfall averages about 10 inches annually. In the southwest there is a small area that receives more than zero recharge that appears anomalous. By reviewing the maximum soil-moisture storage figure, the maximum soil-moisture storage values in this area are significantly lower than the values in the surrounding area. With higher soil-moisture storage values, the calculated recharge in this area also would have been zero. As the maximum soil-moisture storage was calculated from estimates of rooting depth and available water capacity, the effect of these data on the calculation of groundwater recharge is clear. The estimate of maximum soil-moisture storage is one of the weakest components of the water-budget calculations and any data that can improve the knowledge of this component will improve the estimates of evapotranspiration and groundwater recharge.

Recharge by Aquifer System

The project area was intersected with the aquifer system areas from the Department of Land and Natural Resources (DLNR/CWRM). The proportion of the project area within each aquifer system and the calculated average recharge values with and without fog are shown in Table 2. The DLNR recharge and sustainable yield values listed are fractions, based on proportionate area, of the aquifer system total values reported by the State of Hawaii (1990).

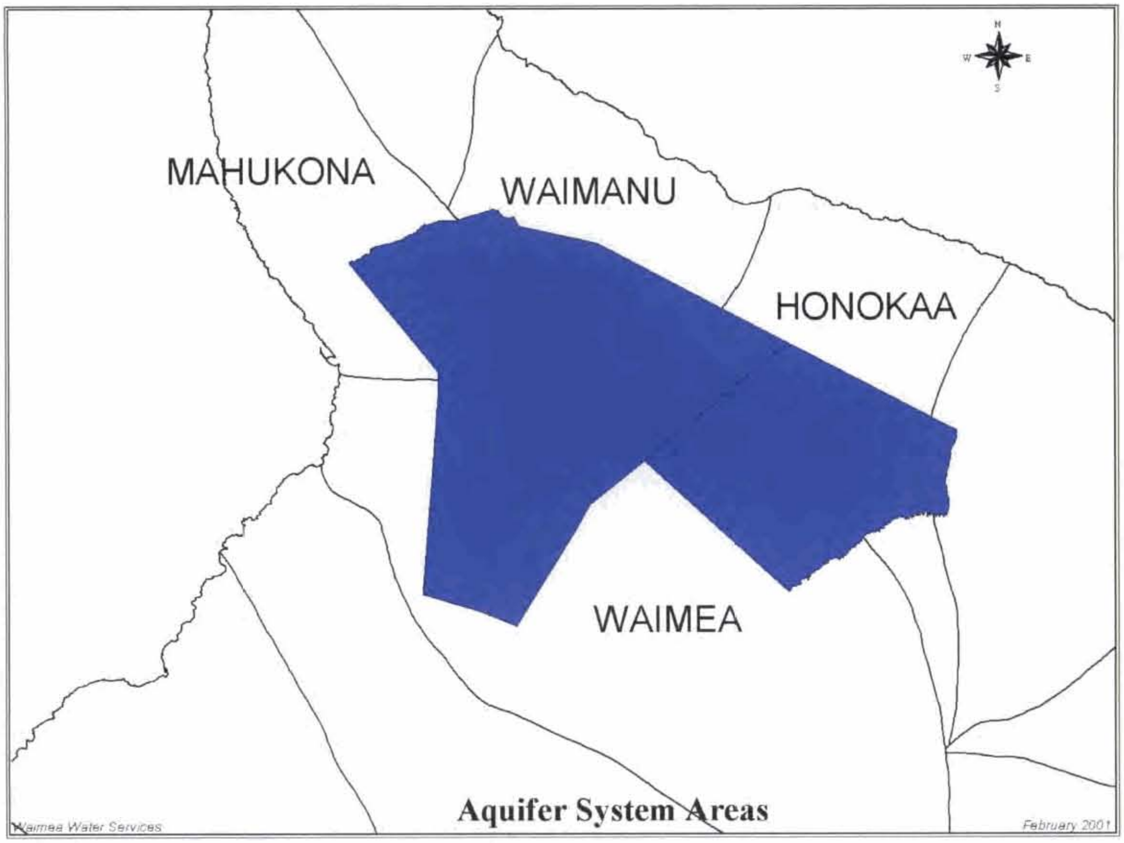


Figure 13

Table 2.

Aquifer System	Percent area of aquifer	Recharge (mgd)	Recharge w/fog (mgd)	DLNR/CWRM Recharge (mgd)	Sustainable yield (mgd)
Honokaa	38.31	9.42	9.42	27.20	11.88
Waimanu	23.41	17.96	31.76	34.41	25.75
Mahukona	37.05	7.15	13.67	14.08	6.30
Waimea	29.02	4.45	5.16	15.67	6.96
Totals		**38.98**	**60.01**	**91.36**	**50.89**

A coarse comparison with DLNR recharge and sustainable yield values can be made by applying the area percentages listed in Table 2 to the total DLNR values for each aquifer system area. This simple analysis shows that the recharge estimated in this project is less than the DLNR recharge values of 27.2 mgd, 34.41 mgd, 14.08 mgd, 15.67 mgd in the Honokaa, Waimanu, Mahukona, and Waimea aquifer system area. While acknowledging the simplicity of this comparison, it indicates that the estimated sustainable yield in the Waimanu and Mahukona aquifer systems could possibly be met if the estimated recharge with fog values are realistic. In the Honokaa and Waimea aquifer systems, the estimated recharge values do not support the sustainable yield estimates. It is likely the groundwater recharge and sustainable yield estimates do not adequately represent the natural system. These estimates will be refined as future water development occurs.

Water-Budget Limitations

Without data that are recorded on a daily or shorter time interval, for all components of the water budget, the results cannot simulate the events of nature. The median monthly rainfall data that were used to create the isohyet map used in the GIS water-budget model adequately represent the average monthly rainfall conditions anywhere in the project area. However, these data do not capture the instances where a large proportion of the average monthly rainfall occurs during a period of a few days. During such an event, soils would be saturated, thereby supporting runoff conditions and evapotranspiration would be suppressed. In the generally permeable soils found in the project area, water would infiltrate quickly beyond the root zone resulting in slugs of groundwater recharge.

Using a monthly budget essentially treats the hydrologic cycle as a single large event each month. In areas where rainfall is generally negligible except for an infrequent event, the monthly approach could yield satisfactory results. However, this scenario does not represent the occurrence of rainfall and fog formation in much of the project area. Simulating a water-budget on an event- or daily-basis would be a useful endeavor to improve the groundwater recharge estimates. Rainfall data recorded on a daily or shorter interval for a short period of less than 10 years are available. These data would be useful in simulating rainfall events, but it should be noted the short period of record must be interpreted judiciously with respect to implying any average characteristics.

Runoff data are also lacking in much of the project area, particularly in the dry areas. Similarly, other than the short record of pan evaporation at the Lalamilo station, evapotranspiration measurements of any kind, or long-term measurements of meteorologic variables that can be used to calculate evapotranspiration are not available.

Soil parameters, particularly available water and root depths, are coarsely estimated due to the lack of field data in the project area. These values were determined from individual soil profiles that are regionalized for the soil series, and thus the calculated maximum moisture storage of the soil at any given point is coarsely estimated. The soil-moisture storage is a critical component in the water-budget model because it directly affects the calculation of both groundwater recharge and evapotranspiration. The collection of any data that can more accurately determine soil-moisture storage would be a significant contribution to the improvement of groundwater recharge estimates from a water-budget method.

Aquifer Storage Volume and Management

In contrast to a basal lens, where the fresh water floats on salt water, high-level ground water is impounded in reservoir compartments which have near vertical boundaries created by volcanic dikes, displacement faults and possibly dense lavas draped over cliffs. The Waimea high-level aquifer system is best described as having boundaries of faults and dikes located within or adjacent to the rift zone of the Kohala Mountain. As mentioned in the chapter on Geology, these compartments appear to be generally oriented parallel to the northwest to southeast axis (see Geologic Map - Figure 3) of the rift zone and straddling it.

A broad rift zone from Mauna Kea extends into the southern portion of the study area. There are no wells in the latter area and there is little known of the high-level groundwater occurrence in this portion. For the sake of this study, water levels in the southern portion (1A, 2A and 3A) have been assumed and are guided somewhat by the known water levels at nearby Waikii.

Storage Estimates

Based on experiences and analyses of high-level groundwater studies around the state and particularly, Oahu, it has been assumed that average reservoir rock porosity is best estimated at about 10% of mass. This would be consistent will the relatively uniform, thin bedded, high porosity lavas of the Pololu volcanic series which make up the majority of aquifer medium. Mink and Yuen (1994) used a conservative specific yield of .025. This latter estimate seems too low given the relative uniformity and high porosity, validated by the ease of deep well drilling, as well as inspection of cutting samples collected during well construction (some samples available in storage at the Hawaii Volcano Observatory of the U. S. Geological Survey). Regardless, the storage calculations are estimates intended as a first approximation of the potential groundwater storage.

The analysis of aquifer compartment storage further assumes that they are uniform compartments and all extend to sea level and not deeper. Such assumptions are only being used for estimating purposes and have obvious limitations. The following table summarizes the storage estimates.

Table 3
Estimated Storage

Unit	Volume (Range) In Trillion Gallons
1	.39 to .412
1a	- .266
2	.662 to 1.060
2a	- .849
3	.771 to .972
3a	- .812
4	.106 to .126
5	.207 to .259
6	.025 to .258
7	.015 to .0065
8	.0033 to .0065
Totals	**2.17 to 4.8**

By comparison, the present surface water storage reservoirs serving Waimea and vicinity totals 150 million gallons. The top fifty feet of the high-level aquifer system contains about 10 billion gallons of storage. The average daily recharge in the primary development area is between 8.5 and 10 mgd (see Water Budget). Waimea presently has a potable water demand of about 1.5 mgd.

These estimates are presented for the purpose of describing the relative relationship of recharge to useable groundwater storage. At the time of the original estimates of sustainable yield (Mink and Yuen, 1992), the high-level groundwater development in Waimea had just begun. These high-level wells have all been developed since 1991. This study can now begin the process of redefining sustainable yield estimates in the area. It will be very important to increase the knowledge of the recharge-storage relationships.

Aquifer storage compartments are particularly suitable in managing the interaction between recharge, demand and pumpage. The normal seasonal variation in recharge and prolonged periods of dry weather can be managed very successfully in a water system which fully utilizes the high-level groundwater storage. This means drawing down the compartment water levels during prolonged dry periods.

The best example of such management is found in the operation of the Waihee Tunnel on windward Oahu. The Honolulu Board of Water Supply constructed a horizontal tunnel bored through a vertical dike, which has a bulk head installed to retain the storage for gravity release on demand. The Waihee experience has proven the value of dewatering over many years, only to have the water levels rapidly restored during wet periods.

High-level aquifers have also been tapped by drilled wells located within the floor of facilities such as the Pahala Shaft and the Molokai Tunnel. The island of Lanai receives the majority of its water supply via wells and a shaft, which develop water from a high-level aquifer system. In both sources, the storage of the high-level aquifers has sustained the well production through long periods of deficient rainfall (Bowles - personal communication).

Other high elevation groundwater resources are now being developed in the Kona and Hilo Districts, some of which appear to be perched aquifers, which should not be confused with high-level aquifers. Perched aquifers have limited storage, are relatively thin and do not extend to sea level.

Definitions of compartmentalized (dikes or faults) systems versus perched aquifers are *essential in establishing long-term water development* programs. The Waimea high-level wells clearly tap compartments, which most probably extend at least to sea level. The Waimea area pumpage is presently insignificant and intermittent and does not provide much horizontal understanding of the relationship between compartments.

Responses to Pumping

Only in the case of the new Waimea Exploration Well (6240-02) and the USGS Well (6240-01) has there been any sign of well interference during pumping tests. The graph (from Nance 2000) of the water levels of the two wells, readily illustrates the impact of the pumping well on the observation well.

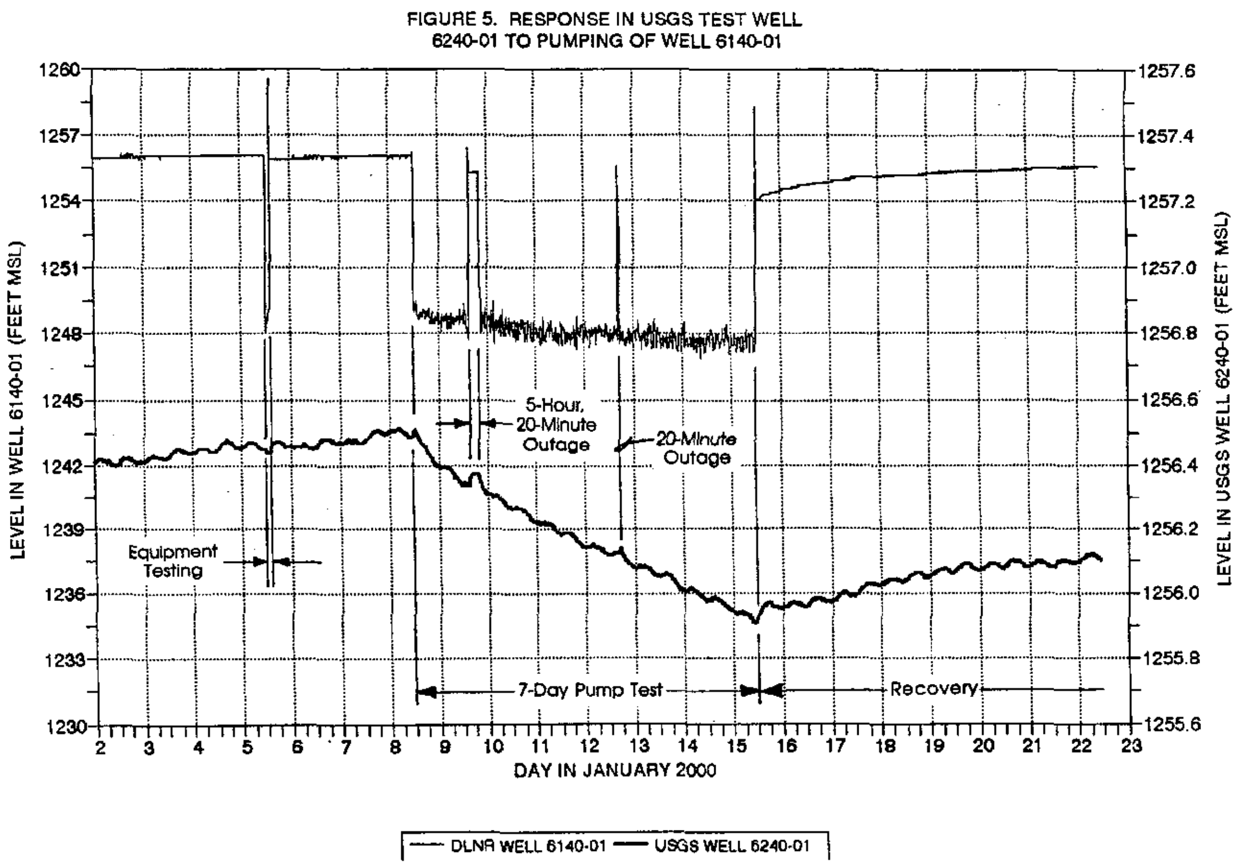


Figure 14

The pumping well had significant influence on the water level (0.6') in the USGS observation well during the test. Note that the slope of the recovery is nearly identical to the slope prior to the pump test. The offsetting drop represents the loss in storage during the test.

The dropping water level of the pumping well also represents the storage lost during pumping. The rate of recovery (slope) is indicative of the aquifer recharge rate. Theoretically, if the drawdown reaches equilibrium (the water level stops dropping) and the water level recovers fully in a time equal to the length of time the well is pumped. The pumping rate will be equal to the recharge rate.

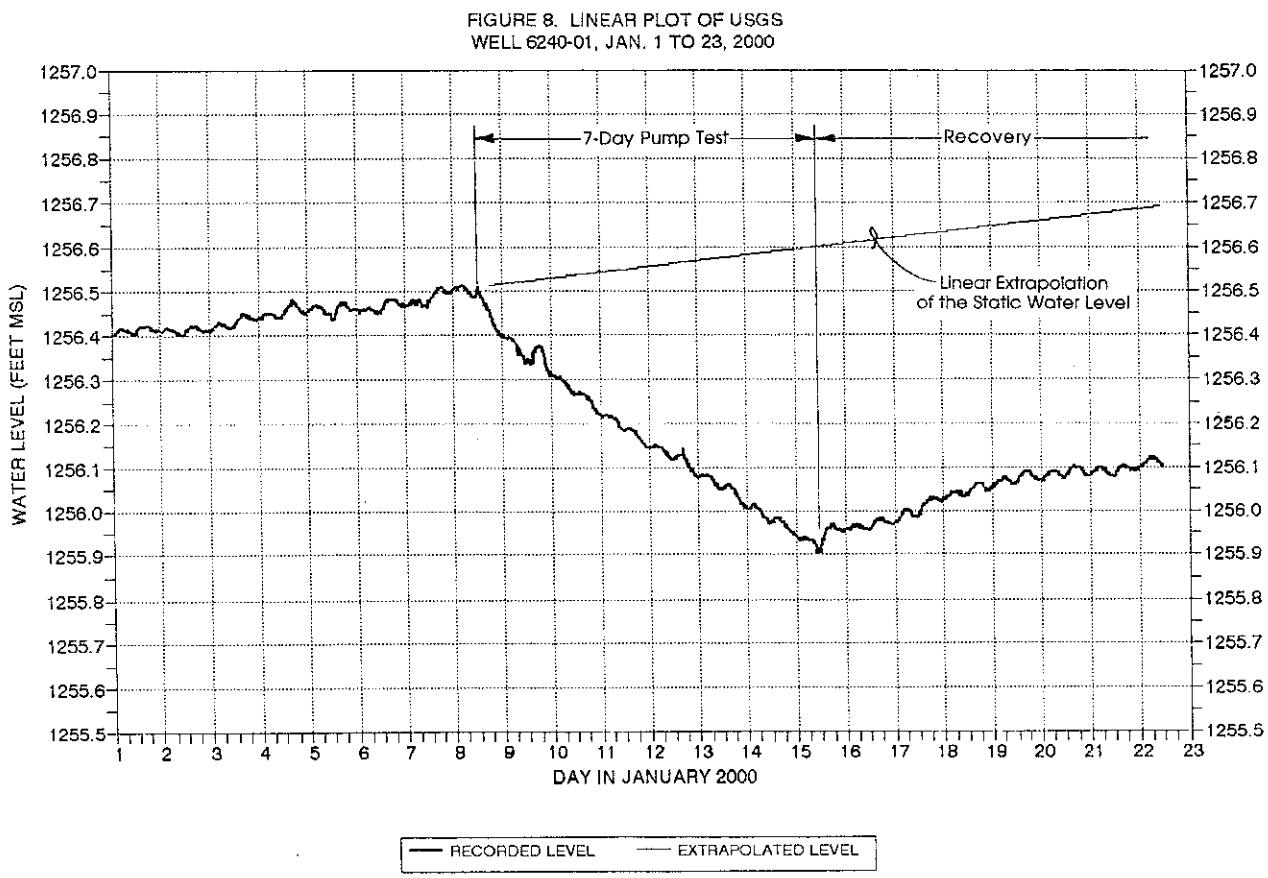


Figure 15

Pumping at a high rate (1000 gpm) has clearly resulted in storage compartment dewatering. The steady water-level drop (about 2') in the pumping well and 0.6' in observation well, followed by the gradual rise after testing, is indicative of the loss from storage during the test. Note that the water level had not returned to its original level following 7 days of recovery.

This same behavior is exhibited in the Puukapu Well (6337-01) when tested at a rate of 700 gpm.

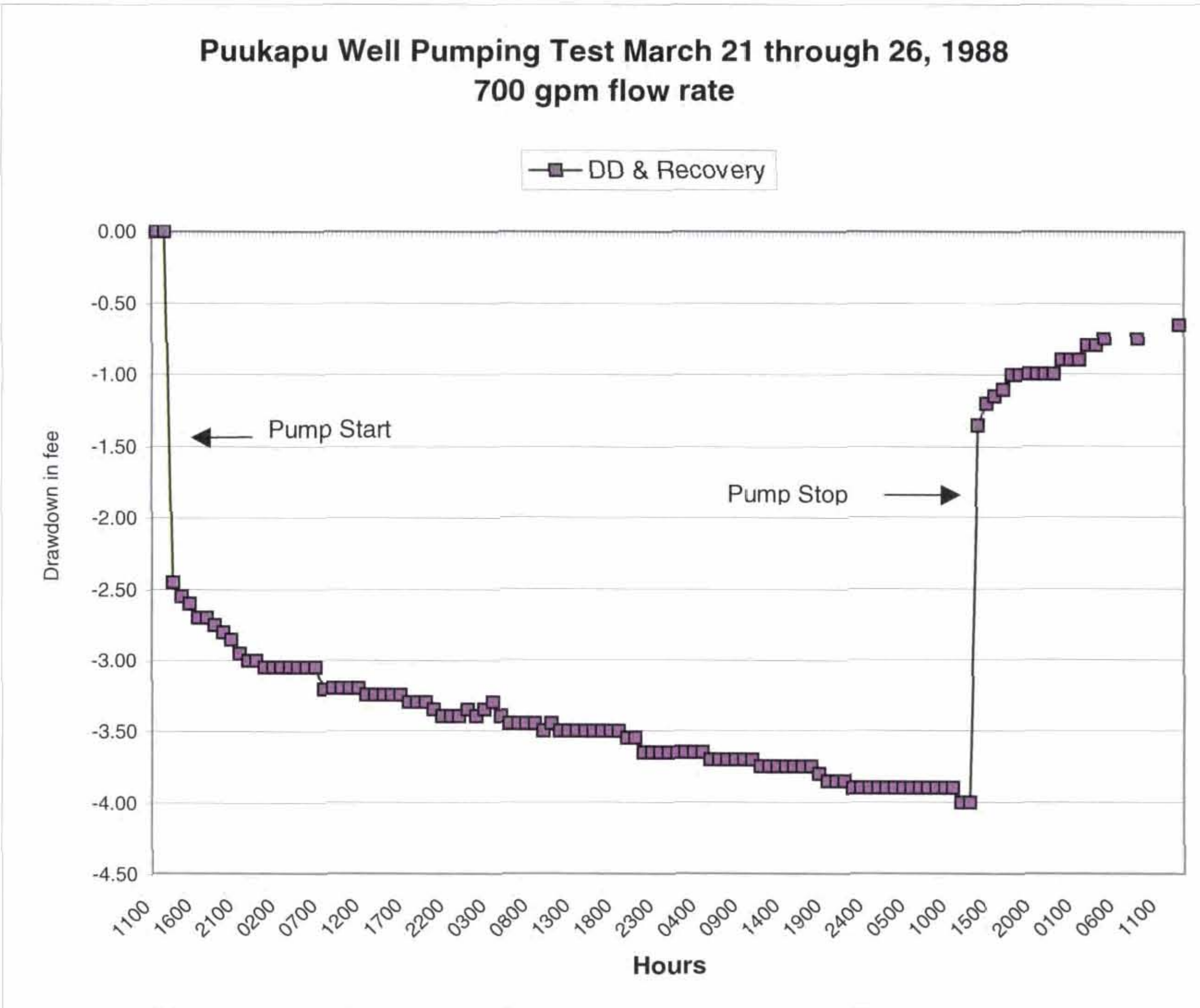


Figure 16

This test also shows the dewatering and recovery characteristic. As the drawdown cone spreads, it will either stabilize when it reaches recharge equilibrium or the water level will continue to drop, indicating that the well is being pumped in excess of the local recharge rate. The cone will continue to spread until it either reaches equilibrium or strikes a boundary causing the water levels to drop rapidly.

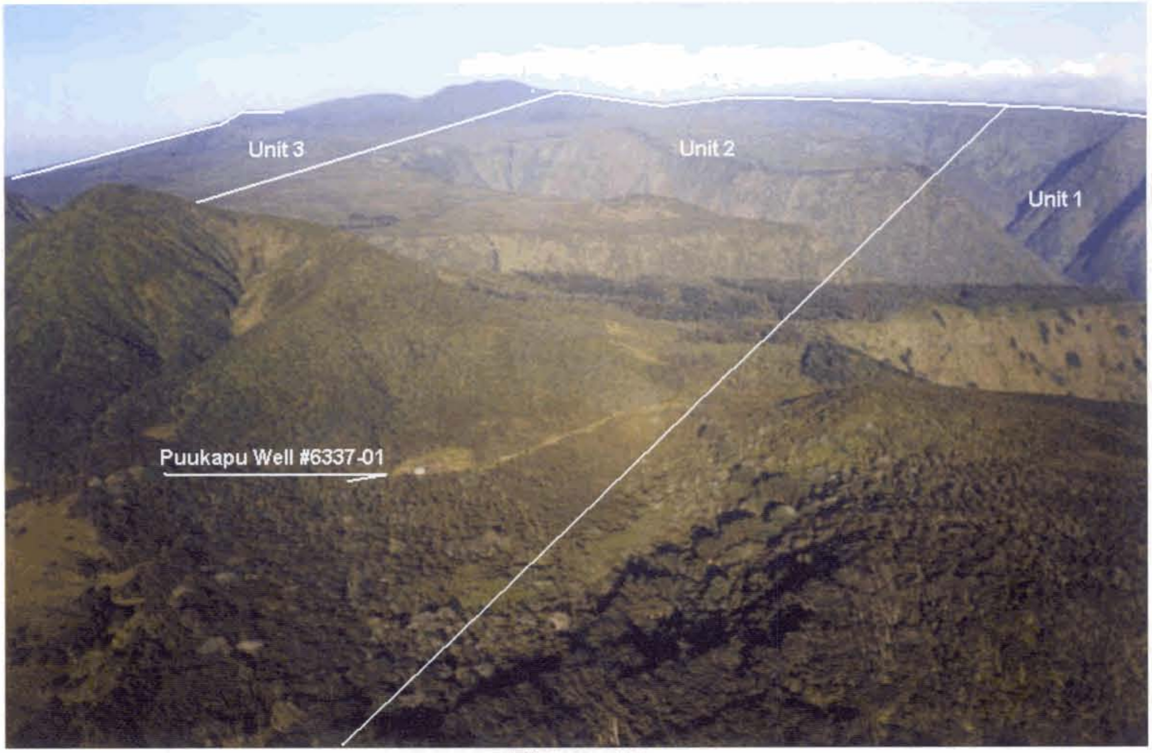


Figure 17

During a 14 day, 674 gpm pumping test run in 1991 on the Parker Ranch Well #1 (6239-02), there was no indication of interference with the USGS Well, some 2500' distant. In fact, the water level in the USGS well was dropping prior to the test and continued to drop following cessation of the test.

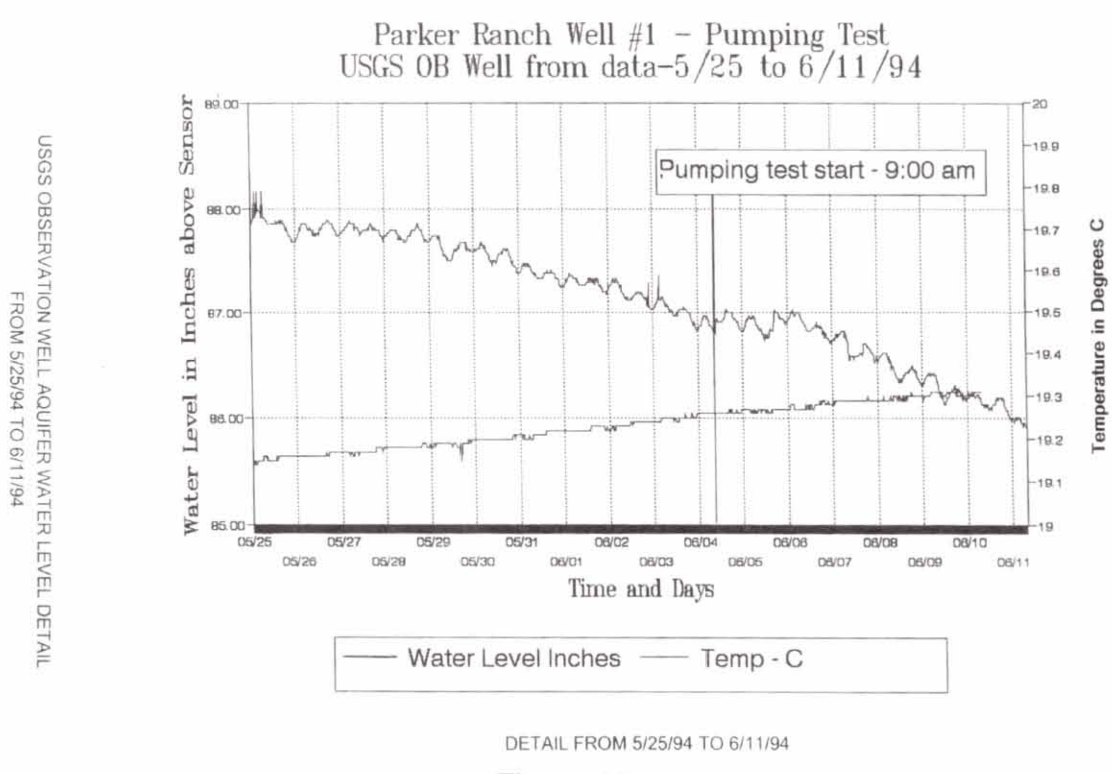


Figure 18

The dropping water level is indicative of the natural leakage from the high-level aquifer compartments as there was no other pumping within the high-level aquifer system at the time. The non-pumping water level in the Parker Ranch Well was about 3 feet higher than the water level in the USGS Observation Well before and after the test. Most probably they are located in separate aquifer compartments, which have little direct hydraulic continuity.

At a pumping rate of 674 gpm, the water level in the pumping well (after the first few minutes) dropped slightly more than 2' over 14 days. The following graph indicates that the water level had not fully recovered after 7 days (10,000 minutes) following the cessation of pumping. This may have been a result over the continuing drop of the background water level as indicated by the falling water level in the USGS well.

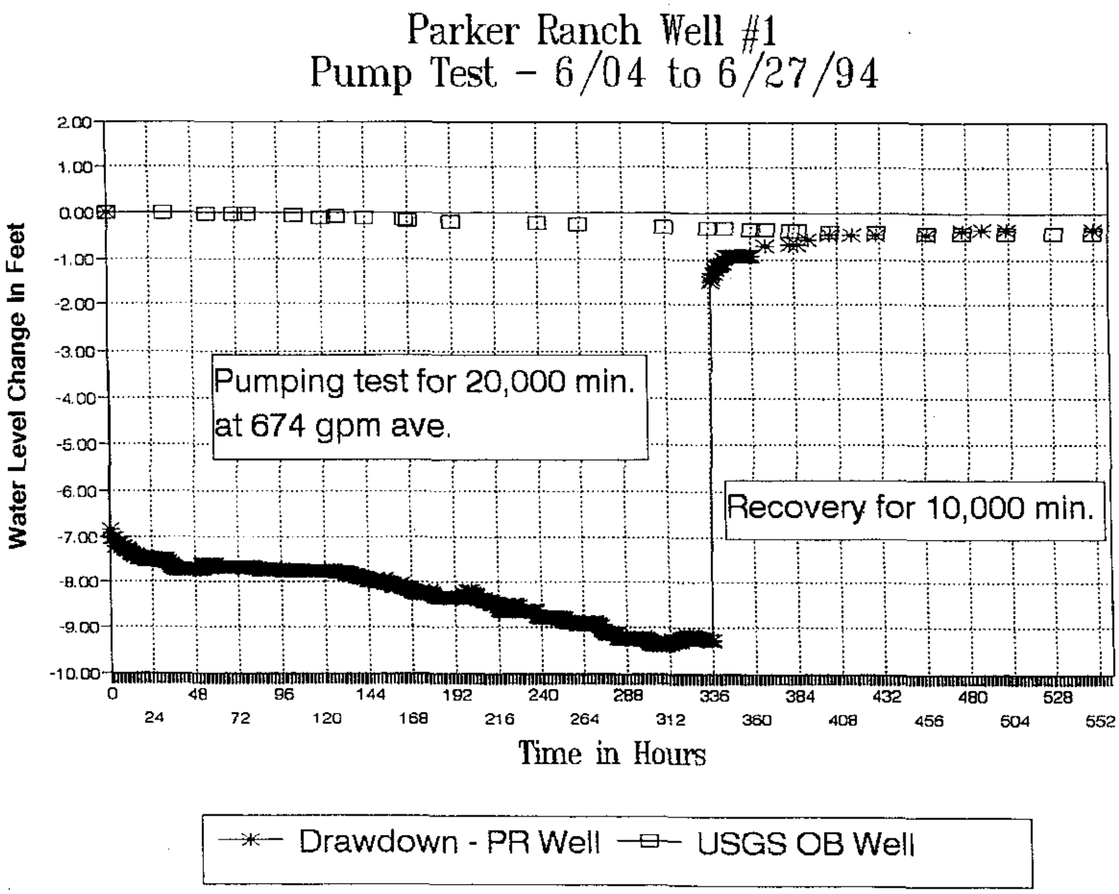


Figure 19

When the Waimea Country Club Well (6235-01) was pumped at a rate of 540 gpm, the total drawdown (including well losses) was 0.7'. There was no additional aquifer drawdown, which could be measured for the duration of the test, and the recovery was immediate. This well is located in the recommended primary development area and is indicative of the high yielding wells expected.

Regional Dewatering Projection

Mink (1994) estimated the transmissivity of the Puukapu Well (2 tests) as from 18,000 to 27,000 sq. ft/day and the Parker #1 Well at about 50,000 sq.ft/day. He further concluded that using 30,000 sq. ft/day was a reasonable estimate for descriptive purposes. Using this information, Mink speculated that with the Puukapu, Parker #1 and a well at the DWS plant site pumping at a combined total 4.5 mgd for 1000 days, the water level might drop as much as 20+ feet. This is highly speculative and did not allow for recharge during that period. Based on pumping responses in similar aquifers on Oahu, Lanai and Molokai, this assumption does, however, appear to be reasonable if recharge is not included.

Aquifer Recharge and Leakage

The reliability of the high-level aquifer system is exemplified by the base flow of the Waipio stream complex. Stearns (1946) estimated the total low flow discharging from the high-level aquifers into Waipio at about 58 mgd. He compared rainfall/runoff relationship from the rainfall events to flows in the Lower Hamakua Ditch (LHD).

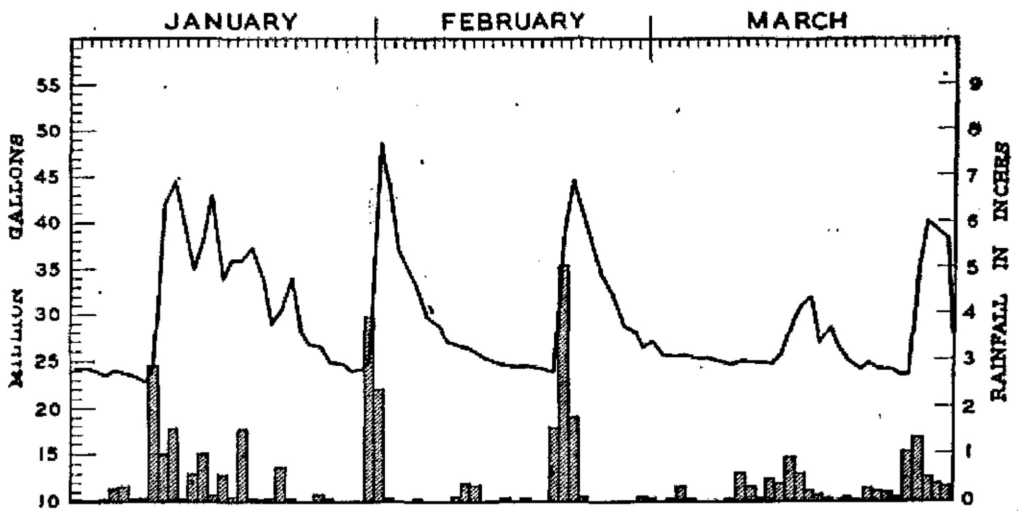


Figure 43. Graph showing the discharge of the lower Hamakua ditch at main weir at Kukuihaele in relation to rainfall at upper Kawainui gage, January to March, 1934.

Figure 20

The low ditch flow (24 to 25 mgd) at Kukuihaele represents leakage from the high-level groundwater storage of the Kohala Mountain. A portion of this low flow is contributed from the study area. The percentage of this contribution is difficult to determine because of the paucity of geologic information on the subsurface structures.

The LHD is constructed within the dike system as mapped by Stearns in 1946 (see Geology - Figure 4). Importantly, the dike and fault trends are generally north-south in orientation and, most likely, the groundwater flow will generally follow the same trend. This would mean that a significant contribution to the LHD low flow is made from recharge to the north of Waipio and is not solely derived from recharge within the study area. This was considered in preparation of the water budget for the primary recharge and development area. The indication is that heavy pumping of the primary area would have little or no impact on the low flow of Waipio.

The conservatively estimated recharge averages more than 8.5 mgd in the primary recharge area of units 1,2, and 3 (see Water Budget - Figure 12). The combination of an estimated storage of 10 billion gallons in the top 50 feet of aquifer, with an estimated average recharge of 8.5 mgd to 15.5 mgd, should be more than adequate to support at least 10 to 15 mgd peak production through substantial dry periods.

High-level Aquifer Limits

While still poorly defined, the high-level groundwater resource area extends well beyond the perimeter of the study area. The Waikoloa Wells, Parker 4 & 5 (5745-01, -02) were the first to verify the existence of high-level ground water on the leeward perimeter. The water level was found to stand at elevation +16' when first measured in 1972 (Bowles, 1972) and +19' in Parker 4 in 1981(Nance and Bowles, 1981). A 64-day aquifer test was run at a continuous pumping rate of 1322 gpm in 1971. Although there was a continuous drawdown, the actual water-level drop between day 6.9 and the end of the test in the 64th day was less than 1'. A third well, Waikoloa #1 (5745-03), was added to the well field in 1989.

Kohala Ranch Well #3 (6649-01) is located just to the northwest of the study area. The water level stood at elevation +136' when it was drilled in 1989. In October of 2000, the water level was at + 143. The well was test pumped at an average rate of 1112 gpm for 7200 minutes. The pumping water level dropped steadily from a drawdown of 3.5' at 100 minutes to 4.1' at 7200 minutes (Nance, 1990). The water-level recovery was apparently fully recovered within 24 hours (1440 minutes).

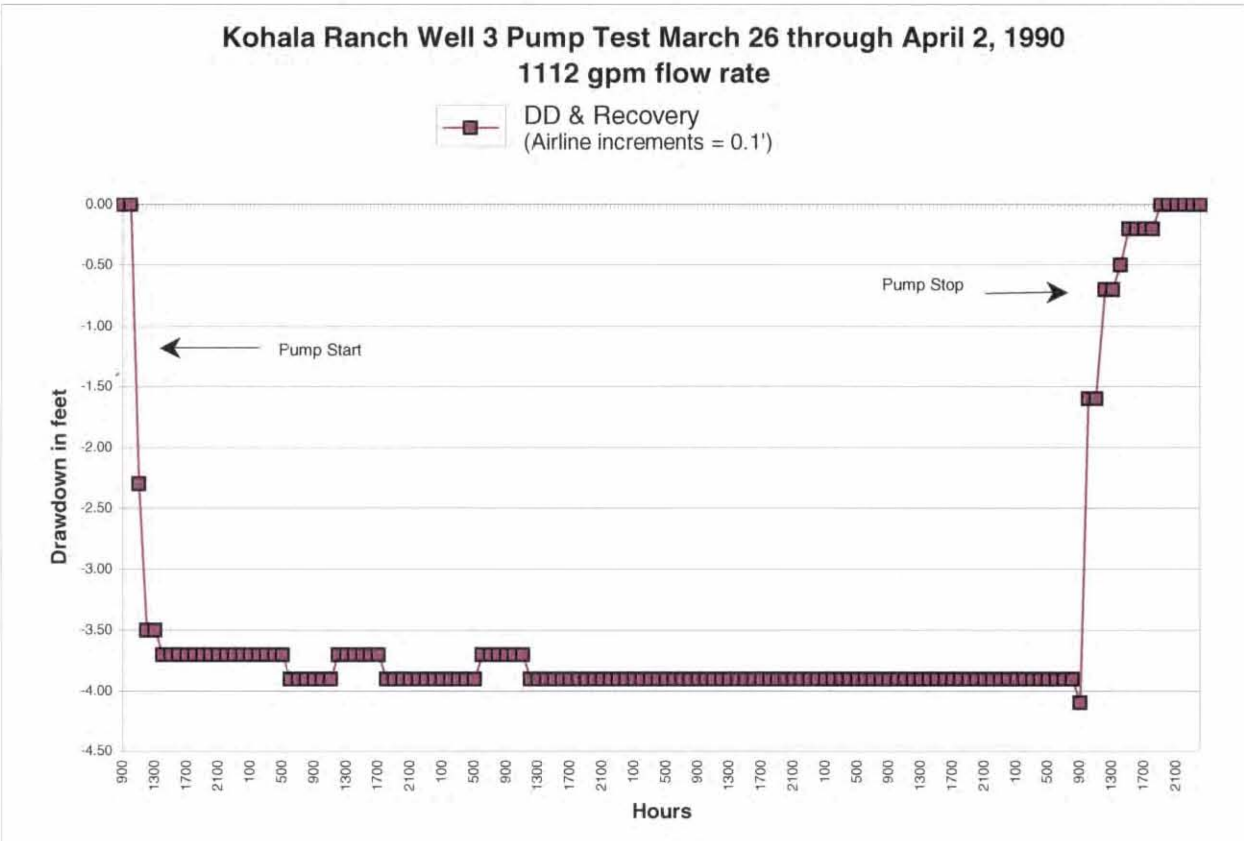


Figure 21

The pumping test results of the Waikoloa wells and Kohala Ranch Well #3 show very similar responses to the tests of the wells near Waimea, and they must be classed as high-level wells. The Waikii Wells (5239-01, -02) located next to the Saddle Road at elevation 4260' struck water standing at + 1507'. These wells apparently have also struck high-level ground water located within the northwest rift zone of Mauna Kea.
The total extent of high-level ground water within the study area can only be estimated at this time. The pumping test results of the various wells show that water levels in the storage system will most probably drop as more wells are pumped. The calculated recharge, using the hydrologic budget method, lies between 39 and 60 mgd. A large percentage of this water can be recovered with proper well siting and groundwater storage management. It is recognized that these estimates will be improved as more water is developed and more data is obtained.

Water Levels and Monitoring

Important to this study is the measurement of water levels in the high-level aquifers. The area has only nine wells which penetrate the high-level aquifer system. Three of these wells represent the Waikoloa potable sources and are situated in the lowest water table (16'+), which may be transitional to the basal lens but is considered by performance and quality to be a high-level resource.

For this study, a water level recorder was placed in the Waimea Exploration Well (6240-02), located next to the back wash reservoir at the DWS Waimea water treatment plant (see cover photo). Satellite recorders were then rotated within, and adjacent to, the study area. In addition, recorded water-level data from the Waikoloa wells was provided by the West Hawaii Water Company. Although it is located just outside the study area, Kohala Ranch Well #3 (6649-01) was included because it penetrates high-level ground water.

Other than the Waikoloa well field, the only well actually pumped regularly is located at the Waimea Country Club (6235-01). A pump is installed in the Puukapu Irrigation Well (6337-01), however, it has not been operated for several years. The Parker Ranch Well (6239-02) has been placed in service occasionally during extreme dry weather and was last operated in the summer of 2000.

The water-level records are of particular importance in developing pre-pumping behavior of the high-level aquifers. This is an extremely rare opportunity in Hawaii to observe an undisturbed aquifer and this study will provide a baseline for future water development.

As additional wells are developed, there will be a greater opportunity to better define the compartmentalization and the interrelationship between the compartments. This study can only begin the definition.

Importantly, there is a direct relationship between the water-level changes and ground-water recharge, which is not presently complicated by pumping. Long-term recording of the water levels will be an essential guide to the full development potential of the high-level aquifers.

Waimea Exploration Well and USGS Observation Well

In early 2000, Nance (2000) presented a water-level graph (on page 40) comparing the water level of Well 6240-01 with the stream flow at the nearby Marine Dam on Waikoloa Stream. During September through half of October 1999, a period of normal rainfall and drainage, the stream flow was fairly steady. In late October the stream flow increased and fluctuated above a stage of 1.6 feet. This was a period of frequent rainstorms arriving in the watershed. By mid-December 1999, the water level in the USGS Well began a rise which continued to the end of the recording period in late January 2000. The only interruption to the rising trend was the direct result of the pumping test of the nearby Well 6240-02 as noted.

From this graph, it appears that the recharge from the heavy rainfall periods is arriving in the high-level aquifer system within 4 to 6 weeks. A long-term water level record is needed to verify such a short response time.

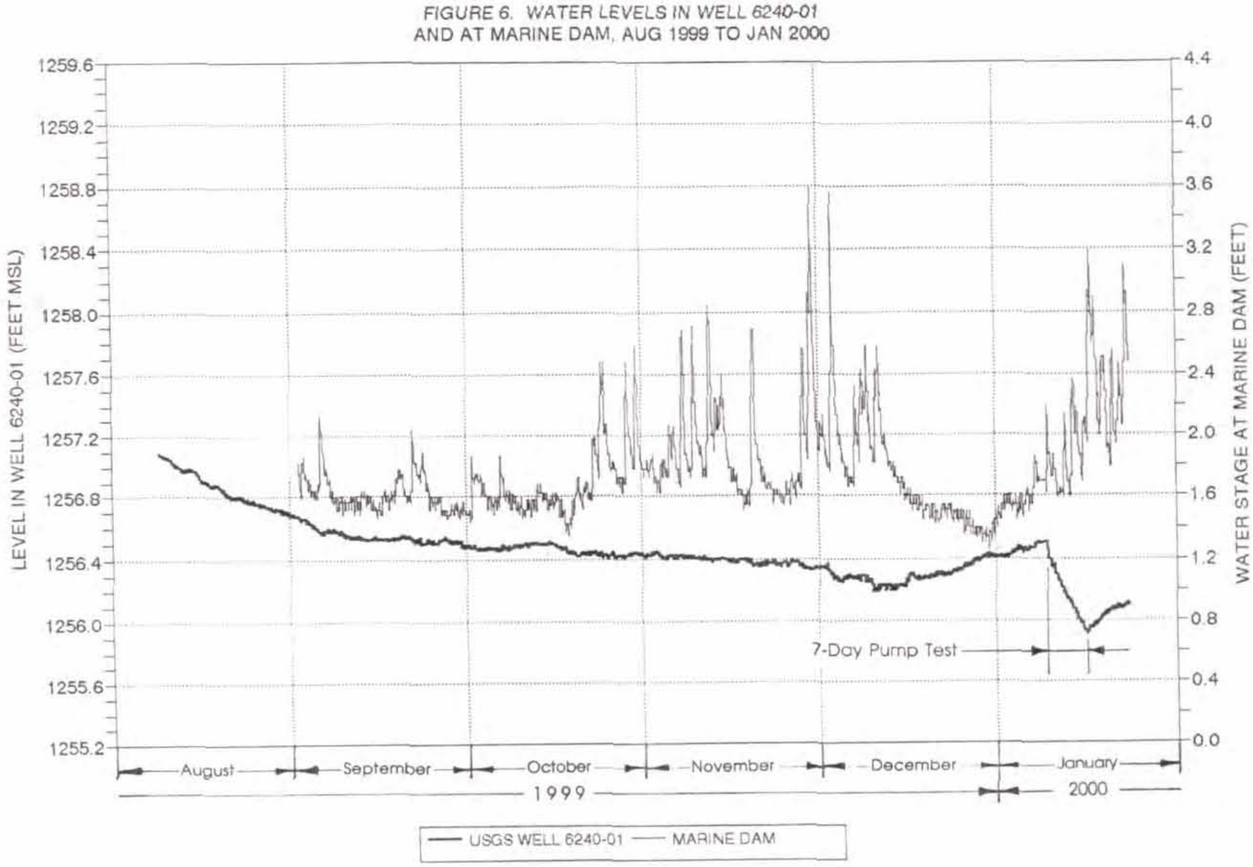


Figure 22

As mentioned in the aquifer storage discussion, the sudden water-level drop in the Observation Well represents the storage lost during pumping, which is superimposed on the rising water-level trend created by an increase in recharge.

The water level recordings made for this study were conducted to provide a better understanding of the broader high-level aquifer system. There were some difficulties in obtaining full records during the study because of the depths of the recorder installations (1200' to 1700'). These difficulties have left some gaps in the data and additional recordings should be made in the future. This study provides some first steps in a more complete understanding of the Waimea high-level aquifer system.

The recorded water-level data from the Waimea Exploration Well (6240-02) has been summarized in the following graph along with a rainfall data plot from the Kamuela Upper HI 97 gage.

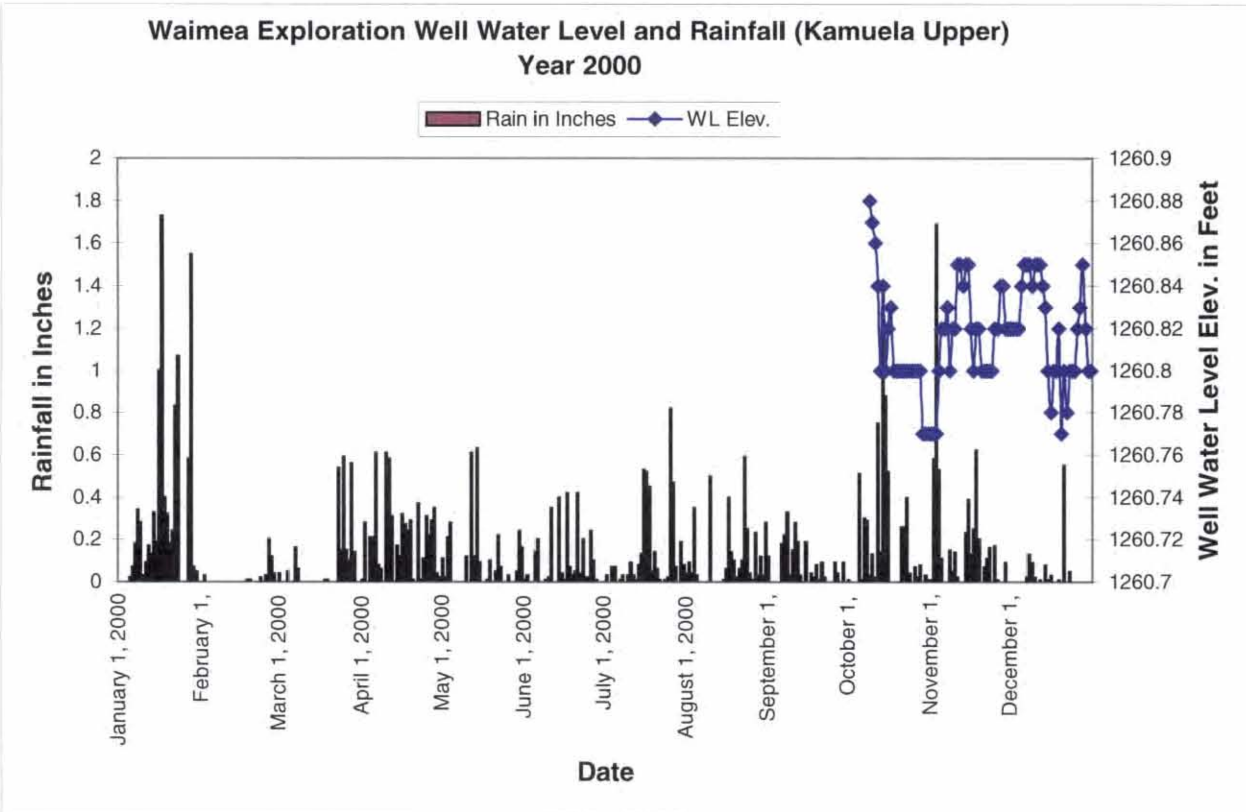


Figure 23

Waiaka Tank Observation Well

A recorder was placed in the Waiaka Tank Observation Well (6141-01) on October 3, 2000 and removed on December 11, 2000. The USGS (Tribble –10/23/2000) measures the water level occasionally as tabulated below:

Date	Time (24 hour clock)	Water Level Elevation (feet)
10/28/99	1100	no measurement: obstruction in well
11/02/99	1100	1245.37
01/31/00	1000	1244.97
04/11/00	1000	1244.90
06/08/00	1425	1244.87
07/19/00	1230	1244.81

The water level was measured at +1244.81' on October 26, 2000 when the recorder was removed. A summary of the recorded data comparing the Waiaka Well with the Waimea base well is presented in Figure 24 (on page 42).

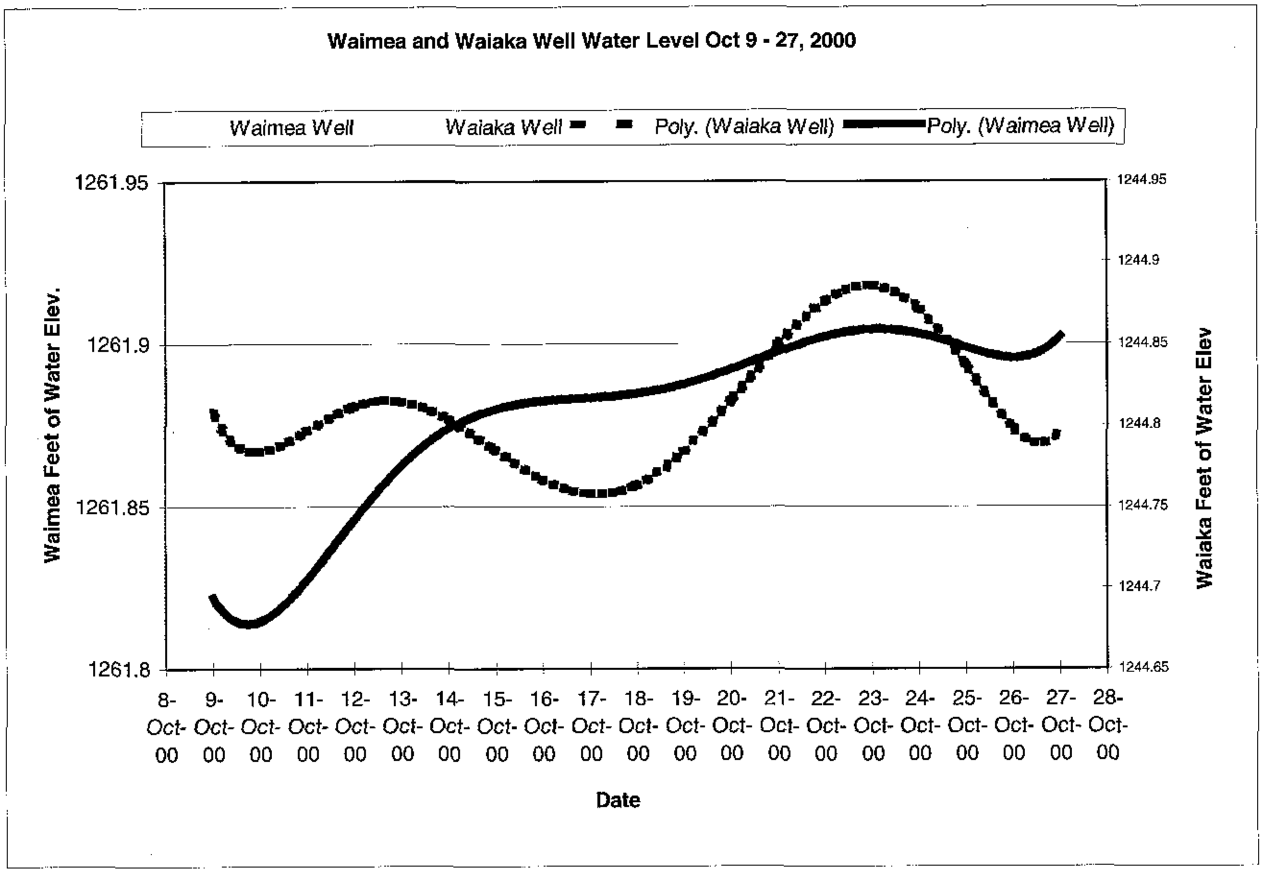


Figure 24

The water levels were measured with a Solinst water-level sounder. The water level fluctuations appear to be similar between the two wells with a slight time lag. Such a lag would be expected if the wells are located in separate storage compartments or are more remote from the source of recharge.

Kohala Ranch Well #3

A recording was also made of the water level in the Kohala Ranch Well #3, even though it lies outside the study area as it represents the low rainfall northern portion of the high-level aquifer. The water was found to be standing at +141', some 5' higher than the first measurements in 1989' (+136'). The Well was observed from September 8 to October 3, 2000 during which time the water level rose about 0.2'.

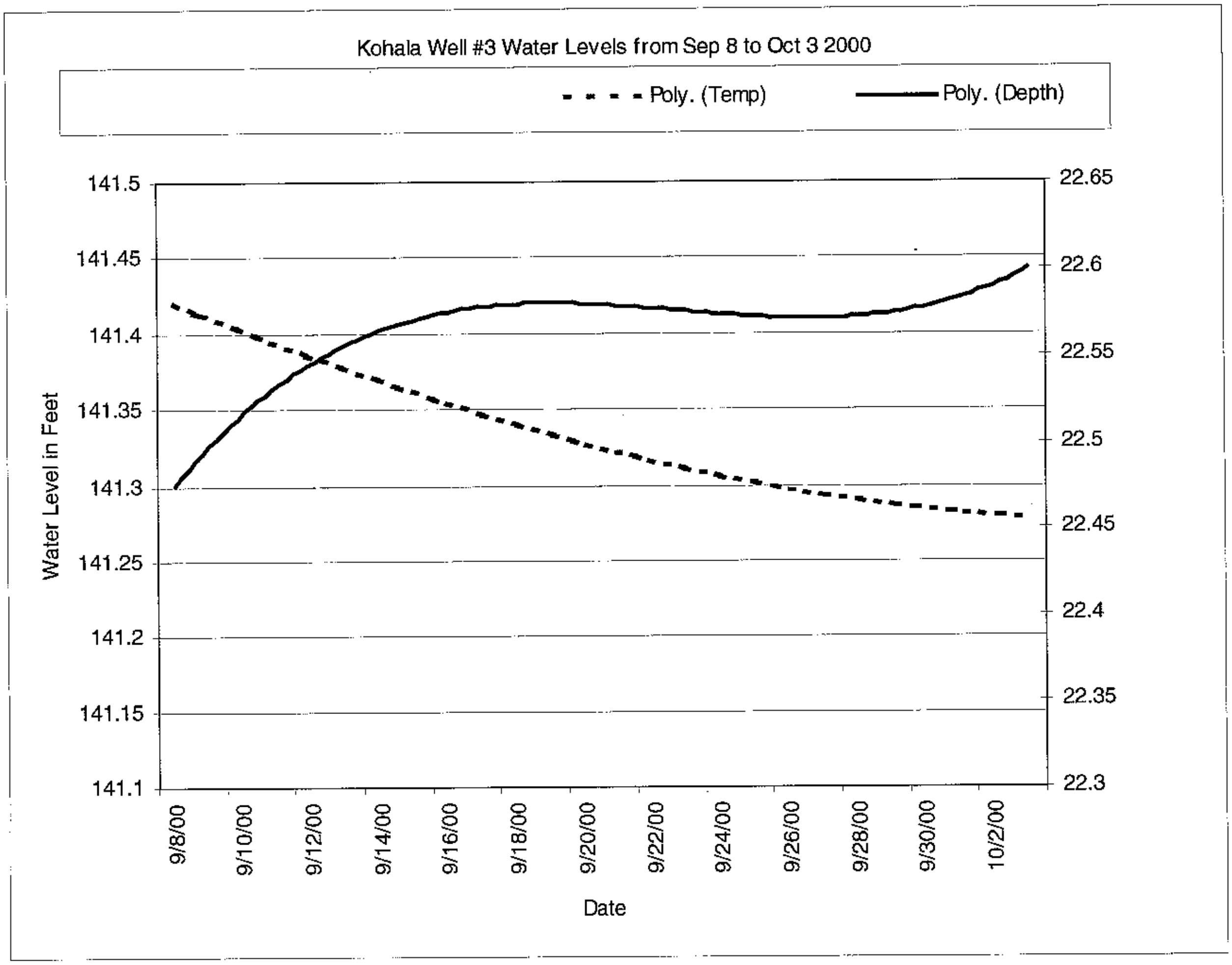


Figure 25

The rainfall mauka of the well, in the next table (Figure 26), as recorded at the Kahua Ranch headquarters gage, shows that there was more rainfall in the preceding months of July and August than in June or September. This implies that there was probably some recharge occurring at the crest and windward slope of the Kohala Mountain and that recharge was migrating into the region of the Kohala Ranch Well #3.

Kahua Ranch, Ltd.
Headquarters
Monthly Rainfall in Inches

Month	Year 2000	68-Year Average
January	6.13	7.15
February	0.08	5.22
March	1.82	6.34
April	3.36	5.69
May	1.09	3.04
June	1.32	2.25
July	2.19	3.21
August	2.07	2.77
September	1.39	1.88
October	2.72	2.77
November	5.19	4.66
December	0.92	6.78
TOTAL	**28.28**	**51.72**

Figure 26

The storage compartments' water levels are indicative of the response to recharge and discharge, whether by pumpage or leakage. Long-term measurements of water levels are very important in evaluating aquifer management practices and there is a pressing need to begin such monitoring before heavy pumping is introduced. Overall, the various measurements made during the four months of field survey showed relatively stable water levels having a range of about 0.2'. The USGS/WWS water-level measurements of the Waiaka Tank Well showed a range of 0.56' from October 1999 to October 2000. Because there was no pumping in the vicinity, this range is probably representative of full storage compartments and reflects the variation in recharge versus a fairly constant rate of leakage. A regular water-level survey (at least quarterly) of all accessible wells in the high-level aquifer system should be instituted soon.

Water Development and Exploration

Water development of the Waimea high-level aquifer has already begun although very little pumpage occurs presently, except during droughts. Parker Ranch has developed one well (6239-02) and has reserved potential well sites along the old government road as part of its 2020 plan.

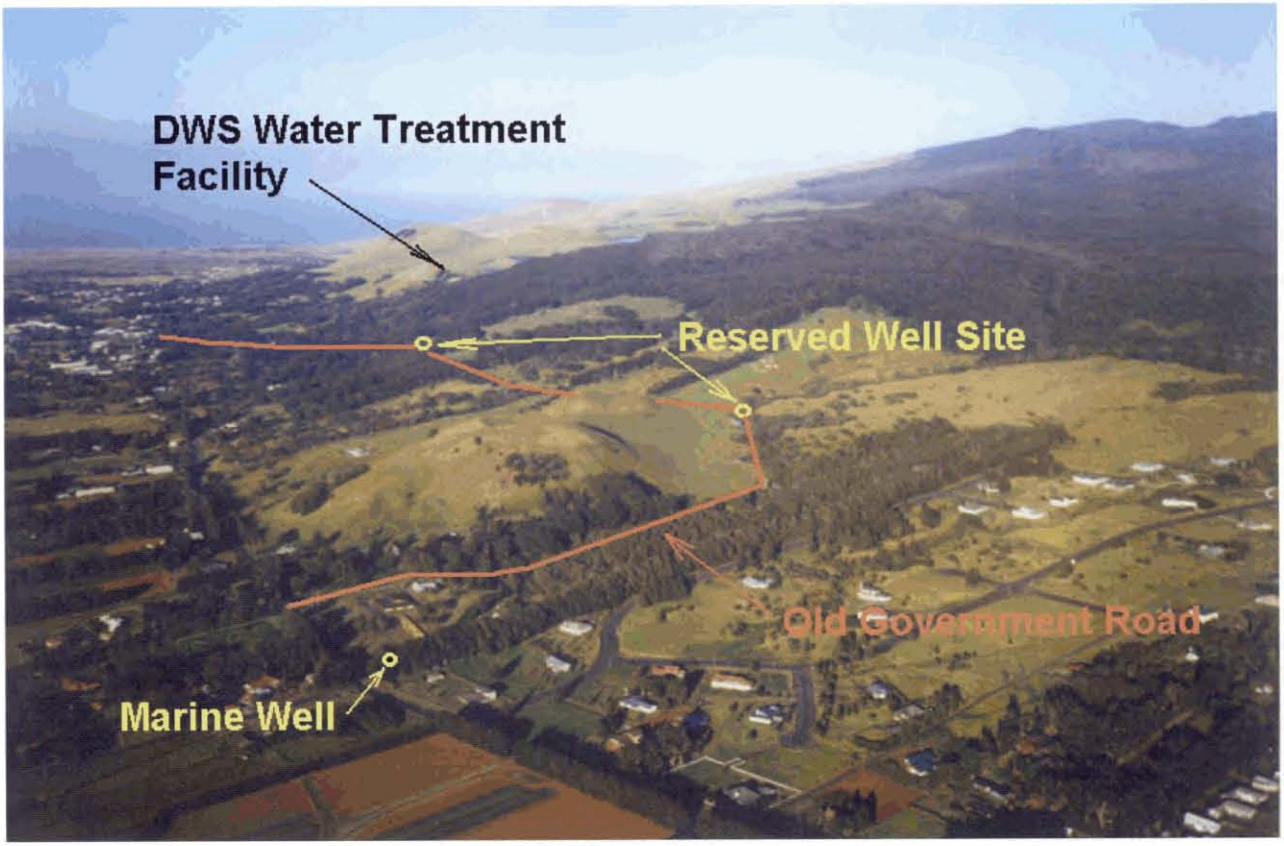


Figure 27

The DWS is considering a production well at Waiaka Tank adjacent to the USGS Observation Well (6141-01). Waimea Exploration Well (6240-02) was completed in 2000 and will eventually become part of the Waimea system.

Pumping Lifts

The wells drilled to date have been built for the primary purpose of supplying water to the Waimea service area controlled by the 4 million gallon covered reservoir (overflow at elevation 3052'). A lower pressure zone begins at Waiaka Tank (O.F. 2521.5') on the leeward side of Waimea.

Tank B of the Lalamilo basal well field begins its service at O.F. 1103'. It is most probable that long range planning will continue these basic hydraulic zones with intermediate zones between them. In the case of Lalamilo, the pumping lift is approximately 1093', a well drilled at the Waiaka Tank would have a minimum pumping lift of 1278'.

By comparison, the Waimea Country Club Well (6235-01), if pumped in transmission along Mamalahoa Highway (over the highest point at elevation 2885' to the Waiaka Tank) would have a pumping lift of 1228'.

The net result is that developing the high-level aquifer in the region of the Mud Lane-Mamalahoa junction could require as little as 193' of pumping lift more than the Lalamilo well field, plus whatever pipeline friction might be designed in. Importantly, the fortuitous high-level aquifer beneath the Waimea Plains opens up a very significant alternative resource to serve the leeward coast.

Figure 28 (on page 47) is a cross section from the shoreline on the Hamakua coast, through Waimea, the Waikoloa wells (Parker 3 & 4) and to the leeward coast. The dashed line shows the surface projection of the buried Kohala Mountain.

3-D TopoQuads Copyright © 1999 DeLorme Yarmouth, ME 04096 — 1 mi Scale: 1 : 200,000 Detail: 10-0 Datum: NAD27

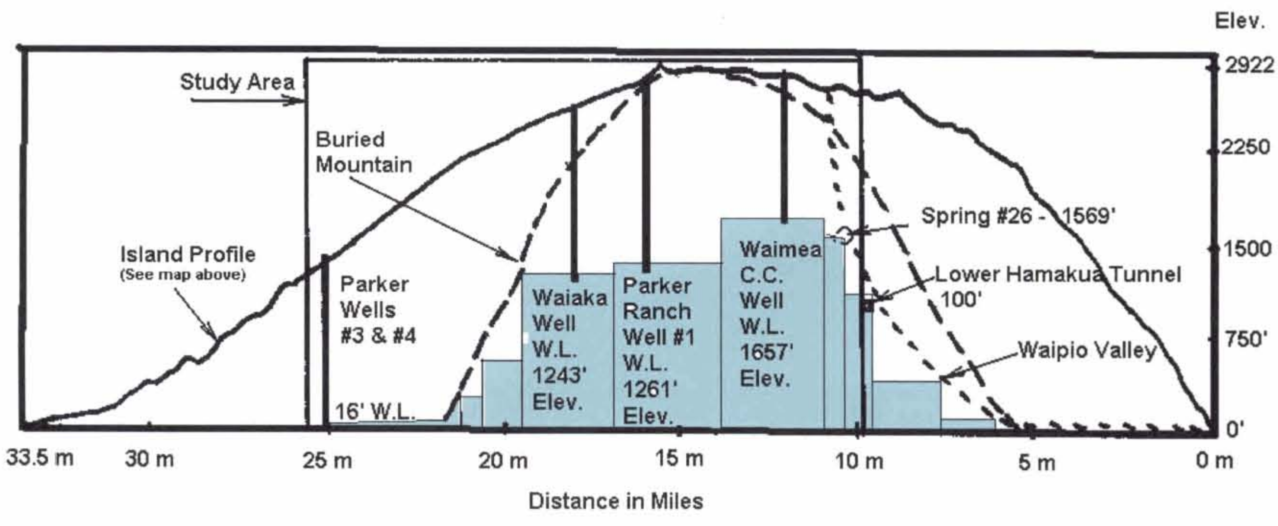


Figure 28

Transmission Routing and Tanks

Development of the high-level aquifer for leeward service should be master planned with a new transmission line to follow the routing of the Waimea Bypass Highway beginning in the vicinity of Mealani. A storage tank should be planned at the crest, at about elevation 2960', in the vicinity of the road to Mana. This would also be a critical point of departure for the existing water service along the Mana Road supply to the Department of Hawaiian Homes Lands.

The transmission routing should continue along the Bypass Highway to elevation 2500' between the Waimea Airport and Puu Pa, where a large storage tank (say 1 mg) would be constructed with an over flow elevation of 2521.5' (Waiaka Tank O.F.). This tank (Puu Pa) would become the source for a transmission line headed makai along the Kawaihae to Waimea Bypass (see DWS Water Master Plan – December 1971).

If a major well field source was built between Mud Lane and Mana Road, the anticipated pumping lift would be about 1280' (assuming a 20' aquifer drawdown).

Exploration

In considering the long-term perspective of high-level development, it will be necessary to determine the water levels across the Waimea saddle from east to west. The significance of the apparent graben (geology) in directing the groundwater flow should be confirmed. An exploration well is needed in the vicinity of Kuhio Hale, or the old Marine Well (6239-01) could be deepened, to establish the transition in water levels between the east and west sides of Waimea village. An alternative would be to explore the rift zone in the vicinity of Mana Road and the Waimea Bypass.

As indicated by the comparison of pumping lifts, there may be as much as 300' to 400' difference in the water table elevations, with the highest levels found between Mamalahoa Highway and the Puukapu Well on the east side. This difference translates into about 100 hp per 700 gpm (1 mgd) pumping rate, which may prove to have great value in operating cost (developing the east side rather than the west side).

Figure 29 (on page 49) shows additional sites, which should be explored in the future to establish the water table elevations. As mentioned in the chapter on Storage, the totals were estimates from assumed water levels and the data must be refined as the high-level aquifer is developed.

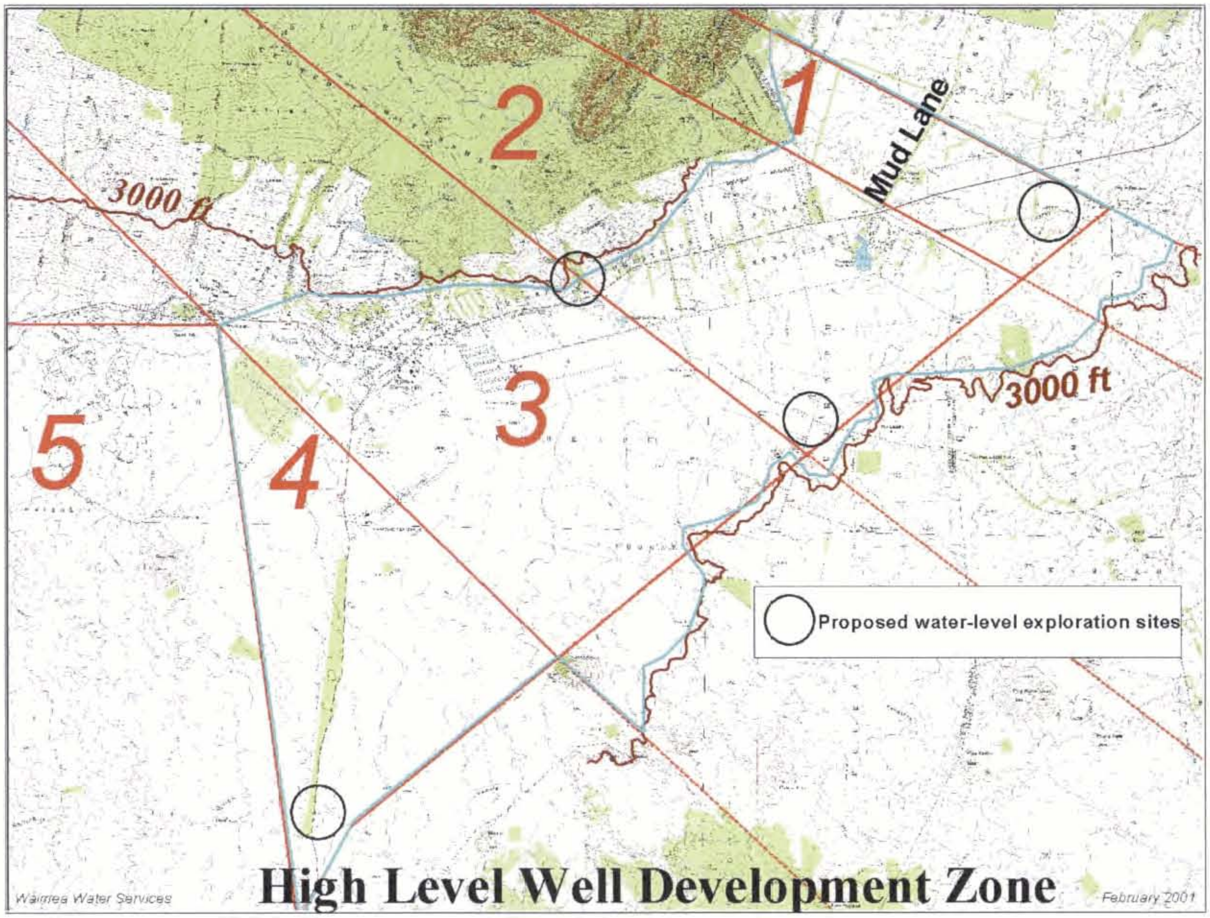


Figure 29

Production Well Sites

For the purpose of this report, no specific well sites are shown other than those recommended for exploration. The actual well sites should be predicated upon their location with respect to transmission and storage facilities and the hydraulic or service zone the water is needed.

A water system master plan should be prepared along with the selection of the specific well sites. Land for storage reservoirs and well sites should be defined and, if not purchased, they should be earmarked in zoning maps. It may be feasible to buy easement options with full purchase at the time of development.

In the chapter on the Water Budget, the recharge for the primary development area was estimated. This was done to place the likely amount of developable water within the perspective of any demand projections. A water system master plan update is needed to focus on the location of future wells.

Well Spacing and Capacity

At this stage of development, there are few criteria upon which base well spacing recommendations. The lack of interference between the Parker #1 Well and the USGS Observation Well at the WTP site does indicate that it will be prudent to consider a spacing on the order of 2000' or so. The pumping impact between the new State Exploration Well and Parker #1 is unknown. Once these two wells are activated, some criteria might be developed.

As a precautionary step, it would be appropriate to have a minimum of 2000 feet separation between production wells until there is a better basis from which to make a judgment. With aquifer compartments formed by the volcanic dikes and faulting, predicting a specific separation using standard calculations of transmissivity or other aquifer coefficients is somewhat risky. Dewatering of a compartment should be the primary focus as wells are constructed and tested.

A typical high-level well should be planned at capacities of about 700 gpm with adequate spacing between wells. Additionally, the pumps should be submerged to about 100' below the water table to take advantage of the groundwater storage drawdown during prolonged dry periods.

Each well should be properly equipped with accurate water-level measuring instruments and duly recorded.

Power Considerations

As is typical, power lines are normally placed along primary road access. It may prove beneficial for the DWS to seriously consider the ownership of its own power lines in the future to provide more flexibility in operations. This is particularly true once the water system begins to drop down the leeward slope where energy recovery becomes feasible at pressure reducing stations. To accomplish this, the master plan transmission lines may want to be offset from the normal highway routes.

A major consideration should be the integration of time of day pumping in the master plan process. There is a definite need for a change in the on-demand power uses of today. At the power rate structure presently in existence, the maximum use of groundwater storage in the high-level aquifers can produce significant reductions in power cost through well investment in combination with increased daily surface storage. The Waimea system, with a 4 mg covered storage reservoir, is particularly suited to such management.

Any system master plan should place close attention to both energy efficiency and to power cost in operations. It is clear that energy projects, contracted off the HELCO grid, will become commonplace as the cost of oil continues to rise. A solar farm, which is in service during the day, can be used to deliver the water during the day at a fixed cost. The leeward coast of Hawaii is one of the sunniest spots in the world. Parker Ranch is placing a combination solar and wind farm into service to help offset the cost of power being used to boost water up the slopes of Mauna Kea. It is typical of the hybrid power systems of the future.

All future water development will depend on energy for pumping power. The availability of sunlight compels a need to integrate direct solar power production into the system plans. Again, a DWS-owned power line would greatly enhance its long-range management flexibility in water production.

Water Resource Quantity

The estimated direct recharge to the primary high-level resources (elevation 1600' to 1700') is from 8.5 mgd to 15 mgd (see Figure 12 – Primary Development Area). Additional recharge may come from nearby tributary study units. Because these are conservative estimates, the actual development potential in the primary area is better estimated initially as having a sustainable production range of from 8.5 to 10 mgd.

As exploration and pumping better define the extent of the high-level aquifer system and its performance, the developable water resource estimate will be increased in yield potential. The total sustainable yield estimate of the Waimea Plains and its contributing recharge units, as outlined in the water budget, is most probably in the range of from 40 to 60 mgd.

Using the CWRM sustainable yield estimates for the same land area (122,023 acres), as prorated in the chapter on the Water Budget, about 51 mgd would be produced. It is unlikely that this quantity is realistic to consider for actual development, as much of the terrain is unsuitable for water development and transmission. The quantity of ground water migrating into the leeward basal lens must also be considered in any high-level development scenario.

Plans to develop the high-level ground water in quantities on the order of 20 mgd are well within the estimates although there may be physical limitations, such as topography or infrastructure, which would restrict the potential of full utilization of the resources.

Water Quality

The quality of the groundwater developed from the high-level aquifers is exceptionally high for drinking water supplies. There has been no evidence of any organic compounds in the three wells, which have been sampled. The total dissolved solids are all less than 150 mg/L (milligrams per liter) with a chloride content of 10 mg/L or less. At the Waimea Country Club Well (6235-01) in the primary development area, the TDS was 60 mg/L with chlorides of 8 mg/L.

There is no reason to believe that there will be any evidence of surface pollutants. However, any well sites selected should consider nearby land use activities or potential sources of pollution. Proper site design and grout sealing of the well casing are all important. The present land use activities, such as farming, are apparently not contributors of aquifer pollutants.

The single major water quality advantage to high-level sources is the lack of continuity with salt water as might be the case with a basal lens well. Any over pumping will result in dewatering but no increase in salinity.

Conclusions and Recommendations

Geology

New geologic evidence suggests that the Kohala volcano extends beneath the Waimea Plain to at least the vicinity of Ahualoa and may possibly be as far as Hilo Bay.

A graben (down throw fault block) appears to be a factor in a major transition of the high-level aquifer. The water levels stand at about +1657' in the vicinity of Mud Lane in the east and drop to +1243' at Waiaka on the west side of Waimea.

Volcanic dikes and faults within the Kohala volcano and the rift zone on the north-facing slope of Mauna Kea create compartments, which contain the high-level aquifer compartments.

The rift zone and faulting are also dominant in retaining high-level ground water on the leeward slope of the Kohala Mountain.

Water Budget

Two water budget models were calculated: one allocating excess soil moisture to recharge first, and the other allocating the excess to evapotranspiration. The estimated recharge for the 122,023-acre high-level aquifer study area ranged from 40 to 60 mgd.

A primary development area was defined near Mud Lane on the east side of the study area. Groundwater recharge to this portion of the high-level aquifer is estimated as having a range of 8.5 to 15.5 mgd.

Calculations were made with and without a fog drip component.

The study estimates the groundwater recharge without fog drip at 40 mgd, with fog drip at 60 mgd. The CWRM sustainable yield equivalent is 51 mgd when compared on an acreage percentage basis.

Storm events may add significantly to the dry side recharge and these cannot be calculated using monthly rainfall records. Such events should be studied in more detail.

All budget estimates are limited as a result of inadequate data and should be used only for planning purposes.

Storage Volume and Management

Using a porosity of 10% and assuming saturation to sea level, the high-level aquifer storage is estimated at between 2.17 and 4.8 trillion gallons. Approximately 10 billion gallons are contained within the top fifty feet of aquifer.

All of the pumping tests conducted have displayed continuing aquifer drawdown during pumping, typically showing an aquifer storage dewatering.

Parker Ranch Well #1, when pumping for 14 days at 674 gpm, did not have an impact on the USGS Observations Well at the DWS treatment plant some 2500'distant. By contrast, the Waimea Exploration Well influenced the USGS Well, some 300 feet away indicating they were probably situated in the same aquifer compartment.

Drawdown in the Waimea Country Club Well at Mud Lane was negligible at a pumping rate of 540 gpm in contrast to the other production wells, which typically showed aquifer drawdowns of 2' to 4'.

Water Levels and Monitoring

With the exception of the Waimea Country Club Well, the other wells are not yet in production or have only been placed in service occasionally.

The highest water levels are found in the vicinity of Mud Lane and Puukapu at +1657' and 1740' respectively.

The water level at the Waiaka Tank Observation Well stands at +1244.8', some 400' lower than at Mud Lane.

Water-level recordings were made in three wells over 4 months using the Waimea Exploration Well as the base. The water levels in all three wells had fluctuations of only 0.1 to 0.2' and exhibited a slight rising trend.

The water level in the Kohala Ranch Well #3 rose 6' since its construction in 1989.

Long-term water-level observations are needed and should be measured at least quarterly.

Water Development and Exploration

Parker Ranch has reserved 2 additional well sites for their 2020 expansion plans.

A comparison of pumping lifts indicates that the pumping lift at Waiaka Tank at 2500' would be only 200 feet greater than pumping from the Lalamilo basal lens to Tank B at 1180'. A well at Mud Lane could deliver water to the Waiaka Tank with a pumping lift of 1223' when compared with a well at the Waiaka Tank which must lift the water 1278'.

A transmission line is proposed from a well field in the vicinity of Mud Lane along the Waimea Bypass to a storage tank at 2960'. The line would continue on to a tank at Puu Pa at elevation 2500', thence to delivery downhill to the leeward coast.

Four exploration wells are proposed to establish the water levels along the southern boundary of the study area below elevation 3000' and at Mana Road.

The higher water table in the primary development area could save up to 100 hp per 1 mgd delivered to the leeward coast.

Well development should begin with well spacing of at least 2000' and capacities limited to about 700 gpm to prevent too much local dewatering and interference. Enough wells should be built to permit off peak energy consumption. The DWS should consider its own power line to facilitate the development of supplemental energy sources such as wind and photovoltaics as well as energy recovery as the water drops to the leeward coast. Parker Ranch is placing a wind and solar power combination in service to boost livestock water up Mauna Kea.

The estimated total recharge of 40 to 60 mgd is comparable to the CWRM sustainable yield of 51 mgd when prorated on a percentage of the DLNR/CWRM recharge estimate by aquifer segment. Water yield of the primary development area is estimated to range from 8.5 to 10 mgd. Well production of up to 20 mgd can be accommodated during long dry spells through proper use of the high-level aquifer storage.

Water quality is excellent with total dissolved solids of 60 to 150 mg/L. There is no evidence of organic pollutants in the high-level ground water.

Selected References

Bowles, S. P., December 1972. The Potential of Fresh Groundwater Resources at Waikoloa, South Kohala, Hawaii.

Davis, D. A., Yamanaga, G., USGS January 1963. Preliminary Report on the Water Resources of Kohala Mountain and Mauna Kea Hawaii. State of Hawaii, Department of Land and Natural Resources, Division of Water and Land Development Circular C14.

Ekern, P.C. and Chang, J.H., 1985, Pan Evaporation: State of Hawaii, 1894-1983: State of Hawaii, Department of Land and Natural Resources, Division of Water and Land Development, Report R74, p. 171.

Giambelluca, T.W., 1983, Water Balance of the Pearl Harbor-Honolulu Basin, Hawaii, 1946-1975: Honolulu, Hawaii, University of Hawaii Water Resources Research Center Technical Report 151, p. 151.

Giambelluca, T.W., Nullet, M.A., and Schroeder, T.A., 1986, Rainfall Atlas of Hawaii: State of Hawaii, Department of Land and Natural Resources, Division of Water and Land Development, Report R76, p. 267.

Grunow, J., 1960, Productiveness of Fog Precipitation in Relation to the Cloud Drop Spectrum. Proceedings of Cloud Physics Conference, pp. 104-09.

Holcomb, R.T., Nelson, B.K., Reiners, P.W., Sawyer N.L., MS#15965A, Holcomb et al. Overlapping Volcanoes: The Origin of Hilo Ridge, Hawaii.

Juvik, J.O., and Ekern, P.C., 1978, A Climatology of Mountain Fog on Mauna Loa, Hawaii: Honolulu, Hawaii, University of Hawaii Water Resources Research Center Technical Report 118, p. 63.

Juvik, J.O., and Nullet, Dennis, 1995, Relationships Between Rainfall, Cloud-Water Interception, and Canopy Through-fall in a Hawaiian Mountain Forest, in Hamilton, L.S., Juvik, J.O., and Scatena, F.N., (eds.), Tropical Mountain Cloud Forests: New York, Springer-Verlag, pp. 165-182.

Kauahikaua, J., Hildenbrand, T., Webring, M., Geology; October 2000; v.28; no.10; pp. 883-886; 3 figures. Deep Magmatic Structures of Hawaiian Volcanoes, Imaged by Three-Dimensional Gravity Models.

Kinoshita, W.T., Hawaiian Volcano Observatory Contribution No.196. A Gravity Survey of the Island of Hawaii.

Mink & Yuen, Inc., December 1994. Hydrogeological Assessment - High-Level Groundwater in the Waimea – Puukapu Region Hawaii. Prepared for The County of Hawaii Department of Water.

McKnight, J.H., and Juvik, J.O., 1975, Methodological Approaches in Hawaiian Fog Research: Honolulu, Hawaii, University of Hawaii Water Resources Research Center Technical Report 85, p. 34.

Moore, J.G., Clague, D.A., Holcomb, R.T., Lipman, P.W., Torresan, M.E., Journal of Geophysical Research, vol. 94, no. B12, Pages 17,465-17,484, December 10, 1989. Prodigious Submarine Landslides on the Hawaiian Ridge.

Nance, T., Bowles, S. P., June 1985. Proposed Groundwater Drilling Sites on Kohala Mountain Above Waimea Circular C-116. State of Hawaii, Department of Land and Natural Resources, Division of Water and Land Development.

Nance, T., March 26, 1993. Fax Manuscript Report.

Sato, H.H., Ikeda, W.S., Paeth, R.T., Smythe, R.S., Takehiro, Jr., Minoru, 1973, Soil Survey of Island of Hawaii, State of Hawaii: U.S. Department of Agriculture, Soil Conservation Service, pp. 115.

Shade, P. J., 1995 Honolulu, Hawaii. Water Budget for the Kohala Area, Island of Hawaii. U.S. Geological Survey Water – Resources Investigations Report 95-4114. Prepared in cooperation with the County of Hawaii Department of Water Supply.

State of Hawaii, 1990, Water Resources Protection Plan, Volume II, Hawaii Water Plan: State of Hawaii, Commission on Water Resource Management.

Takasaki, K. J., Mink, J. F., November 1982. Water Resources of Southern Oahu, Hawaii. U.S. *Geological Survey Water – Resources Investigations* 82-628. Prepared in cooperation with the Board of Water Supply City and County of Honolulu, Honolulu, Hawaii.

Thornthwaite, C.W., 1948, An Approach Toward a Rational Classification of Climate: Geographical Review, v. 38, no. 1, pp. 55-94.

Thornthwaite, C.W., and Mather, J.R., 1955, The Water Balance: Publications in Climatology, v. 8, no. 1, pp. 1-104.

Tribble, G. W., US Department Of The Interior October 23, 2000. Manuscript Report.

Wahl, K.L., and Wahl, T.L., 1995, Determining the Flow of Comal Springs at New Braunfels, Texas: Proceedings of Texas Water '95, A Component Conference of the First International Conference on Water Resources Engineering, American Society of Civil Engineers, San Antonio, Tex., August 16-17, 1995, pp. 77-86.