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# PART A

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# A Numerical Ground Water Model for the Island of Lana'i, Hawaii



Commission on Water Resource Management

Report xxx-xxx

# A Numerical Ground Water Model for the Island of Lana'i, Hawaii

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# Introduction

## Objectives, Purpose, and Goals

The impetus which generated this study for Lana'i was a request by the Land Use Commission (LUC), State of Hawaii, for Lanai Co. (LCo.), in conjunction with the Commission on Water Resource (CWRM), State of Hawaii, and the U.S. Geological Survey (USGS), to produce a numerical model to further assess the ground-water hydrology of the island and potential impacts of pumping ground-water from Lanai's high-level aquifer. No specific objectives were outlined by the LUC other than to produce a numerical ground-water model.

As such, the objectives, purpose, and goals for this study were kept simple and are as follows:

(1) To provide a firmer understanding of Lanai's ground-water flow system based on the more detailed level of analysis required by a numerical model.

(2) To provide a firmer understanding of the limitations of the existing well configuration as far as developing and utilizing the ground-water flow system.

(3) Produce a two-dimensional (2D) preliminary numerical flow-type model to investigate ground-water heads and flows only, rather than a transport-type model which additionally incorporates solute transport phenomena. Solute transport is not of primary concern at this time. Additionally, the numerical code should have fully three-dimensional (3D) capabilities;

(4) The model shall be at least interpretive and possibly predictive. As described by Anderson (& others, 1992), a model at the interpretive level of investigation requires the methodology and framework for organizing existing data and formulating ideas about the ground-water system dynamics, while predictive models require a greater level of detail and calibration to reproduce actual observed data and responses to pumping. This approach may also be classified as the solution to an identification or "inverse" type problem (Anderson, & others, 1992; Weeks, 1994). Inverse type problems are where stresses, like pumpage, and the resulting responses, or resulting water levels, are known, but the aquifer system itself is unknown;

(5) Lastly, this study provides an opportunity for hydrologists from LCo. and government agencies to work together to produce a useful and meaningful numerical ground-water model to further the geohydrologic knowledge of the island, to provide an additional water management tool for the CWRM, and to give the community of the Lana'i a greater sense of confidence in the estimates for the occurrence and availability of ground-water on Lana'i.

(6) To provide a framework of model reporting requirements for future studies related to ground-water numerical modelling efforts in Hawaii.

## General Regional Setting

The Island of Lana'i is a single volcanic dome which has been extinct the longer than any of the other main Hawaiian islands (Stearns, 1946). Information regarding Lanai's general regional setting are shown in Figure 1.

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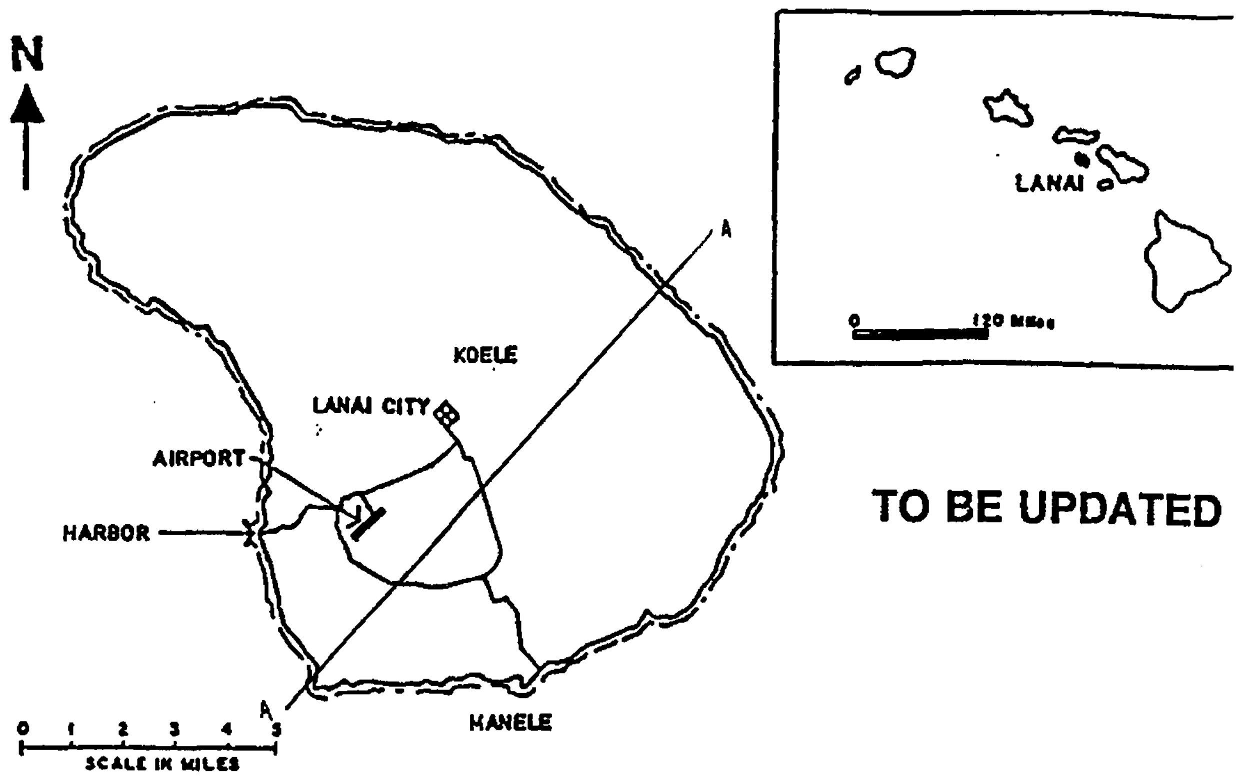



Area = 140.8 square miles, Highest elevation = 3,370 ft., Climate = subtropical

Figure 1. General Regional Setting of Lana'i

# Previous Studies

There have been many studies directly concerning the geology, hydrology, land use, and water resource development of Lana'i which are helpful for producing a ground-water numerical model for Lana'i. These studies are chronologically ordered and a brief description of each is found in Table 1. Full reference of these studies is located in the reference section of this report.

## Table 1. Previous Hydrologic Studies on Lana'i

| Year | Author | Investigated - selected major conclusions |
|---|---|---|
| 1922 | Munro, J. T. | Fog-drip observations. |
| 1924 | Palmer, H.S. | **Ground-water conditions** - no high-level aquifers. |
| 1925 | Wentworth, C.K. | **Geologic conditions** - no high-level aquifers. |
| 1926 | Munro, J. T. | Fog-drip observations. |
| 1930 | Clark, W.O. | Ground-water development - no high-level aquifer but recommended tunneling in Maunalei Gulch. |
| 1938 | Stearns, H.T. | **Ancient shorelines** - similar ocean stands experienced as the island of Oahu. |
| 1940 | Swartz, J.W. | **Geophysical resistivity survey** - profile depth to salt-water/ freshwater interface along transect from Kaumalapau Harbor to the mouth of Maunalei Gulch interpreted as no high-level. |
| 1940 | MacDonald, G.A. | **Petrography** - island building volcanics ceased at primitive stage. |
| 1940 | Stearns, H.T. | **Geology & Ground-Water** -est. recharge 6.46 mgd for high-level aquifer; 21.26 mgd for island. |
| 1946 | Stearns, H.T. | **Short synopsis of Lanai's general geologic history.** |
| 1953 | Stearns, H.T. | Supplement Ground - Water Development on Lana'i - sustainable yield 3 mgd or more. Ground-water loss is heavy on windward side between Maunalei and Lopa and not recovered presently. |
| 1954 | Munro, J.T. & others | unpublished Company internal hydrological analyses (Mink, 1983). |
| 1957-59 | Anderson, K.E. | Three reports cited by Stearns (1959) but not found in research. Defined 'Safe Yield' = 1.9 mgd. |
| 1959 | HI Water Authority | Water Resources in the State - Development of Lana'i groundwater and fog-drip importance. |
| 1959 | Stearns, H.T. | Consulting report - "Safe Yield" described by Anderson (1957-59) is defined by well infrastructure and yield may be increased by adding more wells. Believes little lateral leakance between wells. |
| 1959 | Anderson, K.E. | "Safe Yield" definition letter - concurred with Stearns's definition of "safe yield" and that it can be increased through development of new sources & lateral leakance phenomena. |
| 1960 | Anderson, K.E. | 2 Water supply reports: Safe yield from sources = 2.2 mgd |
| 1961 | Anderson, K.E. | **3 Water supply reports - Safe Yield from sources increased to 2.3 mgd. Ultimate high-level aquifer supply** estimated at 3.6 to 4.8 mgd. Appreciable amounts of Maunalei tunnel water flows by pass water supply system, are not accounted, and probably flow into the sea. |
| 1964 | Ekern, P.C. | **Fog-drip** - rainfall precipitation augmented by 30 inches/yr beneath a mature Norfolk pine. |
| 1965 | Malahoff, A., & others | **Geophysical magnetic survey** - verified Steam's rift zones and additional deep rifts |
| 1965 | Krivoy, H.L. | **Geophysical gravity survey** - verified that main caldera located within Palawai basin. |
| 1967 | Sahara, T.S. & others | **Land classification** - various land use, soil, vegetation, crop productivity, acreage data. |

## Table 1. Previous Hydrologic Studies on Lana'i (Continued)

| Year | Author | Investigated - selected major conclusions |
|---|---|---|
| 1968 | Ching,A.Y. & others | **Land productivity rating** - various agricultural ratings and irrigated acres. |
| 1971 | Bowles, S.P. | unpublished watershed conservation and management program report (Bowles, 1974). |
| 1972 | Foote, D, & others | **Soil Classifications** - island-wide identification and classification of soil information. |
| 1973 | Adams, W.M. & others | **Geophysical resistivity** - optimum drilling sites for high-quality basal water in southeast area between Lopa and Naha. Lower quality between Kaiolohia and Lopa. |
| 1974 | Bowles, S.P. | **High-level aquifer development plan** - infiltration (recharge) estimated at 6.5 mgd. |
| 1975 | Lloyd, R.H. | Description of wells, tunnels, and hydrology - Tunnels began work in 1923. |
| 1982 | Schoeder, T.A. | **Rainfall** - median rainfall isohyets. |
| 1983 | Anderson, K.E. | Water supply review: for planning purposes island freshwater supply estimate is 4.1 to 5.5 mgd Correction to reported Well 3 data by -111 ft. from 4/79 to XI/83. |
| 1983 | Mink, J.F. | **High-level potable supply** - recharge est. 9.3 mgd, sustainable yield est. 6 mgd. |
| 1984 | Anderson, K.E. | Letter report on Mink's hydrologic analysis- disagreed with Mink's approach. |
| 1984 | Anderson, K.E. | Water supply review - wells and infrastructure capable of supplying 2.7 mgd |
| 1985 | Giambelluca, T.W. | **Rainfall** - median and mean rainfall isohyets. |
| 1985 | Anderson, K.E. | Water supply review -wells and infrastructure capable of supplying 2.6 mgd |
| 1986 | Harding Lawson, Ass. | Electrical resistivity investigation - emphasis on locating productive fresh water areas |
| 1988 | Ekern, P.C. | **Evaporation rates** - only one evaporation pan on Lana'i, insufficient to make isogram. |
| 1989 | Anderson, K.E. | **Memo update on high-level water supply** - recharge = 8.89 mgd, S.Y. = 6.22 mgd |
| 1989 | M&E Pacific, Inc. | **Water resources development plan** - Koele and Manele project water demands/development. |
| 1989 | JMM, Inc. | **Lanai Water Use (1948-1988)** - Graphs of ground-water use and water levels. |
| 1990 | CWRM | **Water management area petition** - Lana'i not designated but determined that reasonable hydro logic values are: Recharge = 9 mgd, Sustainable Yield = 6 mgd, and identified a CWRM limit on ground-water use = 4.3 mgd. |
| 1991 | Giambelluca, T.W. | **Drought** - Lanai's most severe occurred in 1931 and lasted 9 months. |
| 1993 | Mink, J.F. | Aquifer Identification and Classification for Lana'i - aquifer boundaries for protection strategy. |
| 1993 | Hobdy, R. | **Forest Reduction** - Feral herbivores are responsible for most of forest damage/recharge impact |
| 1994 | CEES-BGD | TDEM surveys - Areal extent of possible high-level |

There are a few other hydrologic investigations which are not listed in Table 1 since the results have not been formerly published. Well information has been verified by an independent monitor and confirmed by the Lanai Water Committee. Environmental assessments (EAs) for the Koele and Manele project districts were made Lana'i also contain much of the hydrologic information found in M&E Pacific, Inc.'s (1989) water resources development plan.

## Hydrologic Setting and Conceptual Model

A conceptual model is a pictorial representation of a system. It is based on the physical framework observed, which in this case is the geohydrologic conditions on Lana'i, and attempts to link this observed physical framework to an equivalent digital framework in the numerical model. The geohydrologic framework of Lana'i upon which the conceptual model is based is described in the follow subsections

### General Aquifer Characteristics

Lana'i has basal and high-level dike confined aquifers. The actual areal extent of these aquifers is limited by the amount of well and borehole information to date, but a typical conceptual profile of the high-level and basal aquifers for Lana'i is shown in Figure 2. Due to the information gathered from Well 10 the high-level aquifer is now believed to cover more than 15 square miles. The high-level aquifer has both potable and brackish water. The potable water is of very good quality which is typical of high-level aquifers. High-level *brackish* water ($Cl^{-}$>300 mg/l) has only been found in wells located within the Palawai basin area and are accompanied by geothermal heating. Basal water is only brackish as evidenced by wells found both near the coast and over a mile inland at Shaft 1.

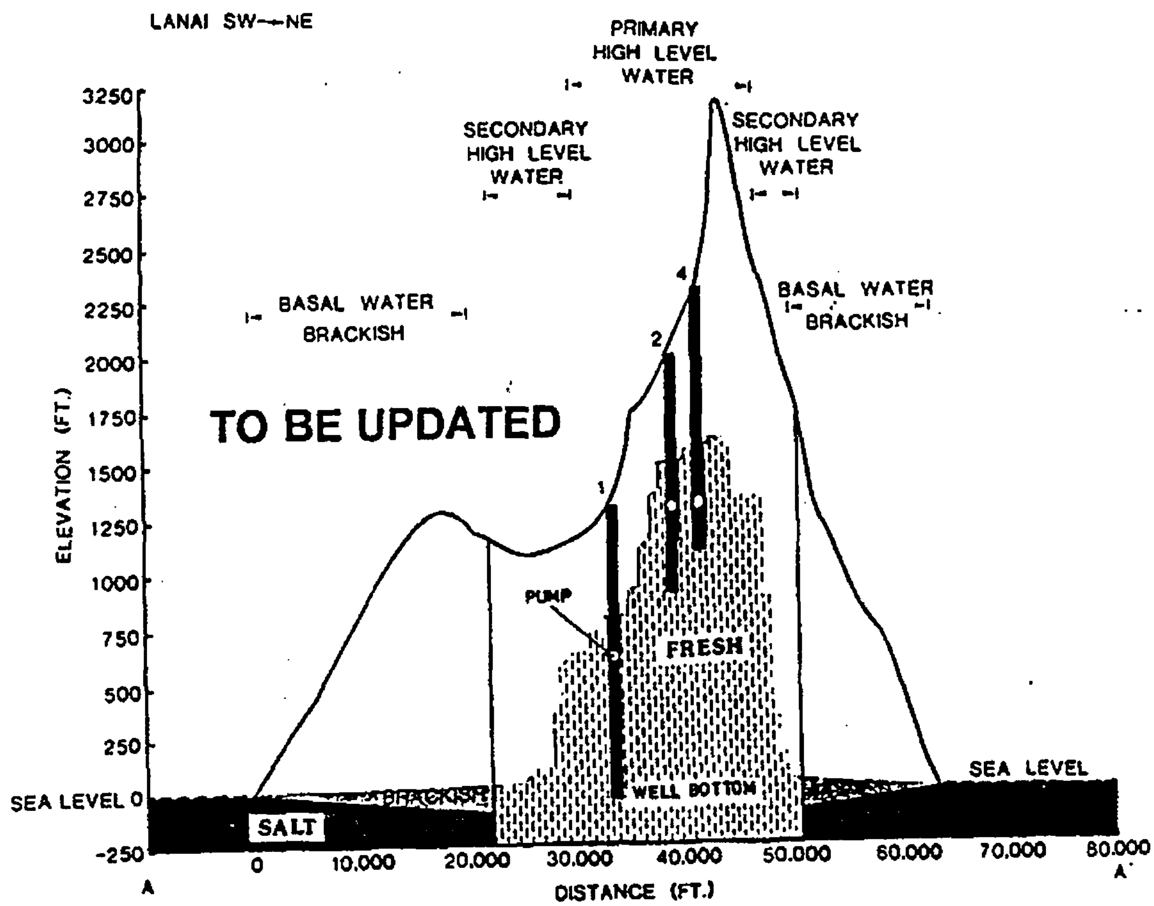



Figure 2. Profile of Basal and High-Level Aquifers on Lana'i

## Conceptual Hydrologic Boundaries

The conceptual hydrologic boundaries consist of *physical* or *hydraulic* boundaries wh define the entire ground-water domain and will internally influence ground-water flow patter Basically, Lanai's major hydrologic boundaries consist of the Pacific Ocean which surrounds a underlies the entire island of Lana'i, caprock-like beach rock along the north shore of the islar three (3) major rift zones which are manifested by observed dike and fault boundaries, and t unconfined water table.

The salt-water of the Pacific Ocean effectively acts as a physical boundary surroundir underlying, and constraining fresh ground-water flow for Lana'i. Freshwater in basal aquifers known to float on top of the denser salt-water to form a freshwater lens according to the Gyhbe Herzberg relationship (DuCommon, 1828; Ghyben, 1889; and Herzberg, 1901). The variat location of streamlines along the bottom of this lens effectively makes this physical boundary hydraulic one too. Through geophysical resistivity analysis of a cross-section of the island co sisting of twenty-one (21) readings between Kaumalapau Harbor to the mouth Maunalei Gulc Swatrz (1940) recorded a maximum thickness of the freshwater lens to be 973 ft. at Station 1 where the maximum depth below mean sea level (msl) to salt water is 948 ft. with a correspon ing water table elevation of 23.7 feet above msl (see Figure 3, pg. 7). However, initial water le els found at three (3) wells located within approximately one mile of Swartz's Station 11, Wells & 7 and Shaft 2, encountered water levels much higher than expected; 1005, 650, and 735 fe above sea level, respectively. Also, only Wells 1, 9, & 10 have been drilled below sea level in tl high-level aquifer but none of these wells have encountered a transition zone or confining botto under the dike confined portion of the aquifer. A later electrical resistivity study by Harding La son Assoc. (HLA, 1986) consisted of thirty-three (33) stations strung out roughly perpendicular Swartz's study along the central part of Lana'i (see Figure 3, pg. 7) also resulted in shallow fre water layers. In some instances, the interpretations by HLA show an absence of high-level fres water between wells which have encountered and produced potable high-level ground-water. fact, the HLA study is careful point out that their interpretations may be erroneous due to the pre ence of the lateral boundaries of dikes and faults. Other resistivity methodologies have been al been used to quantify the depth to salt water, the most recent done by CEEG-BGD (1994) usi the Time Domain Electromagnetic (TDEM) surveys during the formulation of this numeric model. Approximately ninety-nine (99) soundings were taken around the island to estimate tl depth to the salt water/fresh water interface and high-level ground-water occurrence (see Figure pg. 8). The maximum salt water freshwater interface depth below msl was estimated to be excess of 1000 ft. and the initial occurrence of the high-level water begins no more than 3.8 mil inland from the coast anywhere on the island. Like earlier resistivity studies, the presence of di and fault boundaries may distort results in the high-level area. On the other hand, it may me that the Ghyben-Herzberg relationship may not be applicable to the high-level water on Lana'i. is important to note that it has been found that resistivity analysis is of limited value and cann generally be used for depths exceeding 150 ft. below the ground surface (AWWA, 1973). Tl information combined with the fact that there are few wells within the basal aquifer lead one conclude that the actual physical bottom location and profile of the fresh ground-water/salt wa interface island-wide under Lana'i is virtually unknown beyond qualitative description.

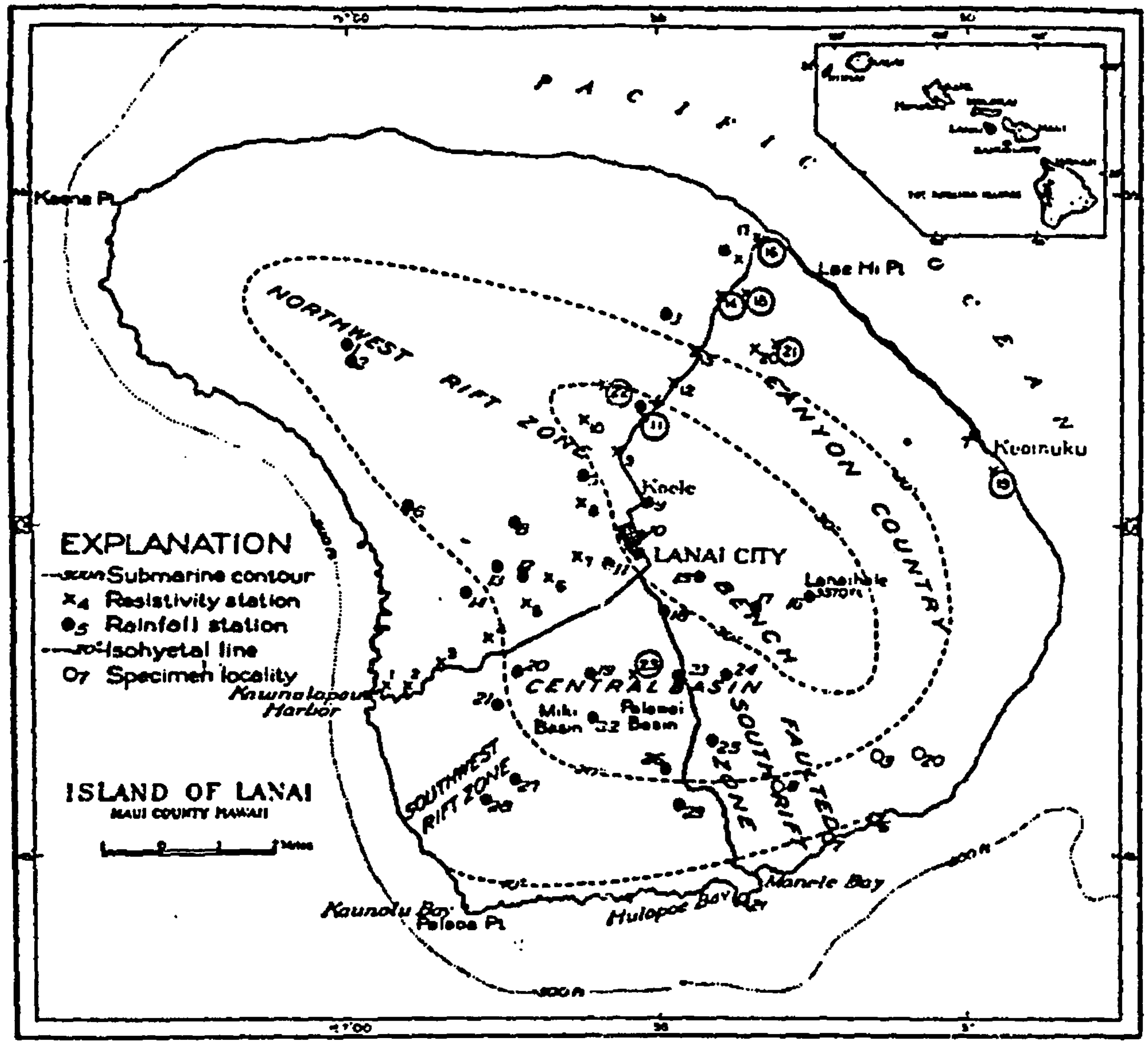



**Fig. 1.** Map of Lanai showing lines of equal rainfall, rainfall and resistivity stations, geomorphic divisions, and 500-foot submarine contour line. Insert map in upper right corner shows location of Lanai in the Hawaiian group.

Figure 3. Electrical Resistivity Study Stations. (Swatrz, (1940) and HLA (1986))

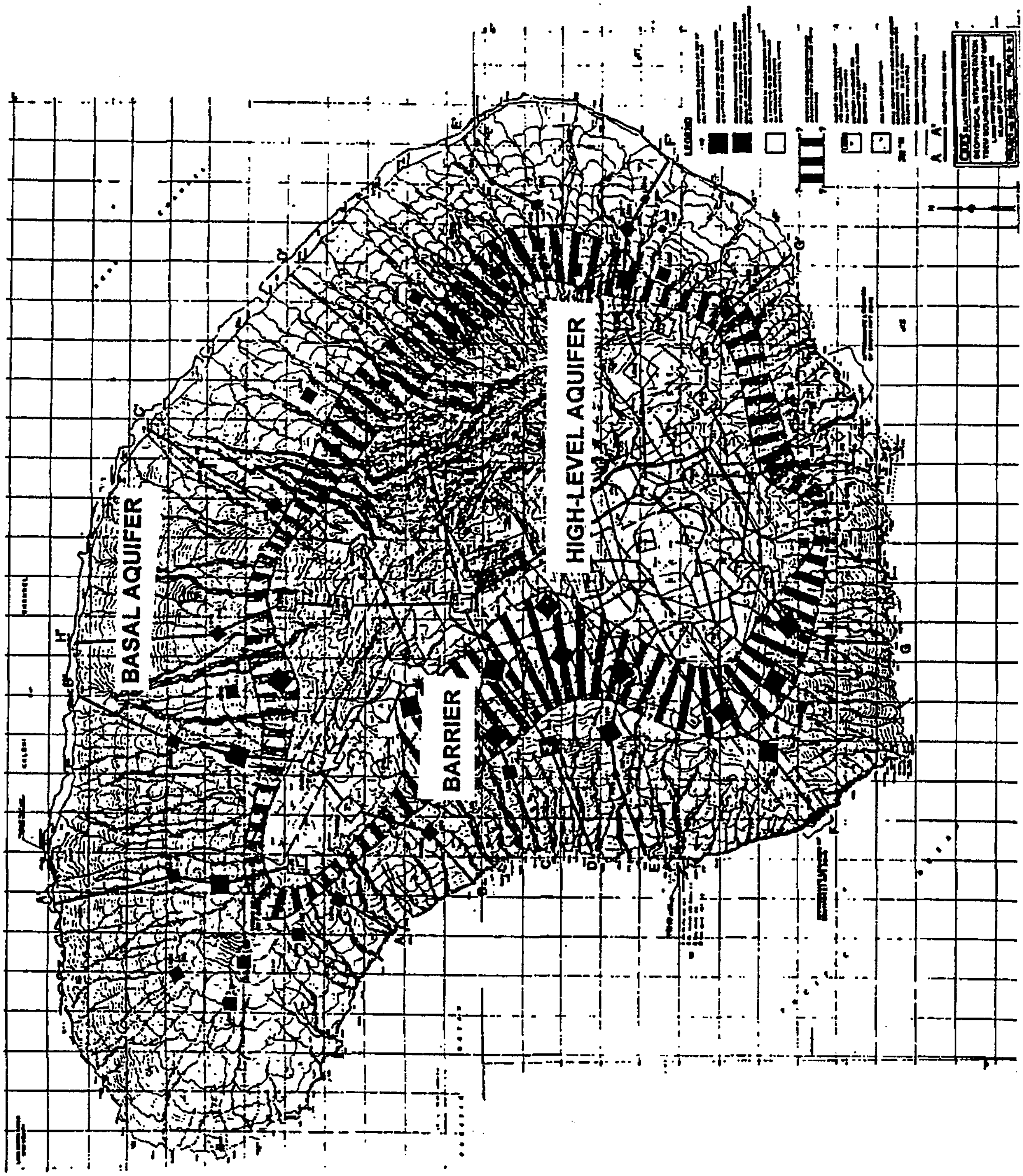
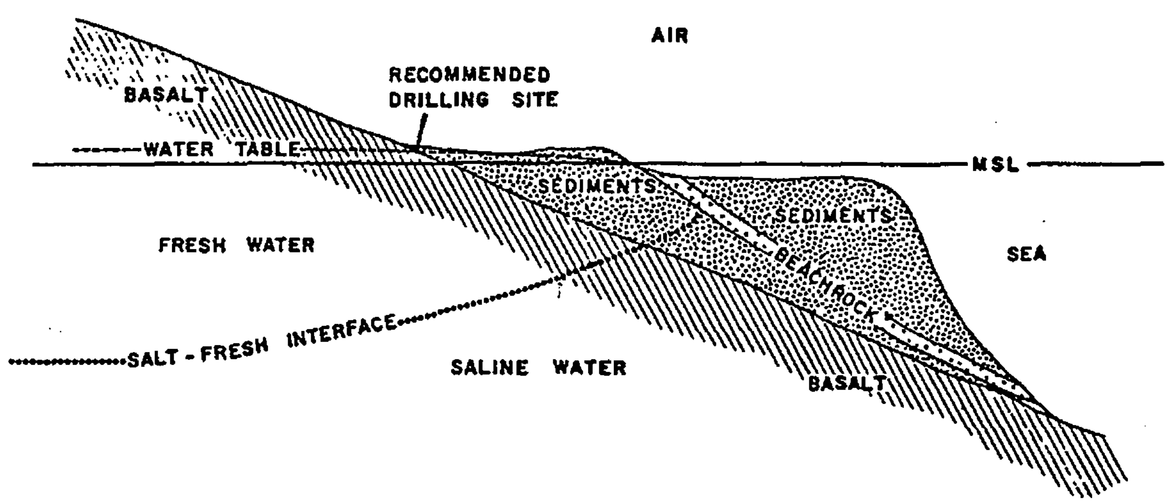



Figure 4. TDEM Study Sounding Sites & Interpretation (CEEG-BGD, 1994)

Ground-water eventually discharges all along the coast of Lana'i through a thin cross-sectional area at the toe of the basal aquifer lens (see Figure 2, pg. 5). There is little or no discernible caprock or alluvial deposits around the steep and rocky southernly shores from the western Palahinu Point to the eastern Kamaiki Point. This southern shore topography is probably the result of the prehistoric landslide known as the Clark Debris Avalanche (Moore, & others, 1989). However, on the northern coast between of these points there are alluvial deposits along the shore which may act like a caprock formation of low permeability Stearns (1940). Stearns attributed the existence of northeastern brackish wells near the shore due to this alluvial geology which would otherwise be contaminated by seawater intrusion. Through resistivity analysis, Swatrz (1940) estimated depth of alluvium at the mouth of Maunalei Gulch at 187 feet below msl. The existence of a low permeability feature was further stipulated by Adams (& others, 1973). According to the results of Adams's geophysical resistivity survey consisting of 176 stations and other field observations the typical shoreline profile from Kaiolohia to Naha is shown in Figure 5. Adams noted that the highest seepage outflow observed along this study area was at Lae Hi Point which happened to be a basaltic outcrop directly in contact with the ocean. This led the authors to believe a beachrock, or caprock, impediment of low permeability exists along Lanai's northern coast's alluvial sediments.




TENTATIVE MODEL OF THE HYDROGEOLOGICAL FEATURE OF THE EAST COAST OF LANAI.

Figure 5. Northshore Beachrock of Lana'i (Adams, & others, 1973)

The principal subterranean boundaries affecting the ground-water flow paths are located in the three (3) major rift zones on Lana'i. Stearns (1940) identified the rift areas as the northwest, south, and southwest rift zones. Within the rift zones the features affecting the flow path of ground-water are intrusive dike and faulting structures. Locations of over 375 exposed dikes and 100 exposed fault boundaries are based on Stearn's geologic mapping of the island (see Figure 6.and help to define the extent of these rift zones on Lana'i. Undoubtedly, many unseen dike and fault boundaries must exist within the rift zones. Dikes may number between 10 to 200 per mile (MacDonald, 1956 & 1970) to 1,000 per mile (Takasaki, & others, 1985). Additionally, a gravity survey by Krivoy (& others, 1965) identified that the Palawai basin contains the island's major caldera and the possible existence of an ancient northwest rift zone and a northwest lobe (see Figure 7, pg. 12). A magnetic survey performed by Malahoff (1973) also concurred with the major rift features identified by Stearns and Kirvoy and, like Kirvoy, indicated the possible existence of northern rift zone not identified by Stearns (see Figure 8, pg. 12). Stearns stated that near Lanai City, the northwest rift zone widens and may be up to 4 miles across as a result of early dike formation with later collapsing and faulting which occurred in a more southwesterly area. As mentioned earlier in this report, the most recent resistivity survey via TDEM (CEEG-BGD, 1994) found that initial occurrence of the high-level water begins no more than 3.8 miles inland from the coast anywhere on the island which indicates a wide areal presence of impediments to ground-water flow. It is well known that dikes are intrusions of dense rock which, when they are sufficiently numerous and intersect, form barriers which impede ground-water flow. The intersection of dikes are such that the can affect both the horizontal and vertical flow of water due to the dip and strike variabilities observed on other islands (Takasaki, & others, 1985; Walker, 1987). Faults may also act as barriers but their effectiveness as impeding boundaries it is not as well demonstrated as dikes. However, Stearns observed and described fault breccias to which he attributed low permeability and stated that they should act like dikes in restricting ground-water flow. It is important to note that these breccias contained fragments of the intrusive rocks associated with dikes which is evidence that dikes are also shattered by faulting which may actually increase permeabilities of dike formations in some instances.

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Figure 6. Geologic Map of Lana'i (Stearns, 1940)

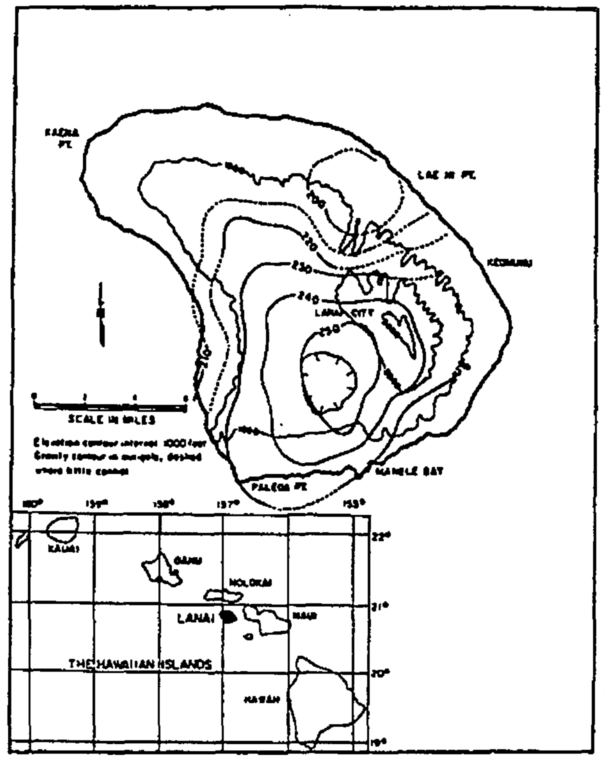



Figure 7. Gravity Survey of Lana'i (Krivoy, & others, 1963)

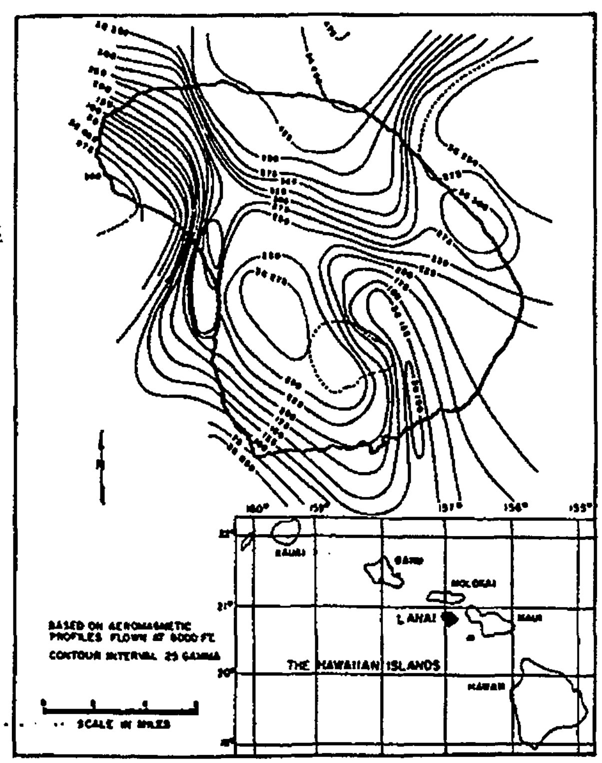



Figure 8. Magnetic Survey of Lana'i (Malahoff, & others, 1973)

The water table makes up the final hydrologic boundary for Lana'i across which net fluxes from recharge and pumping occur and vary spatially and temporally. One could consider the isograms of hydrologic processes affecting the spatial distribution of recharge, namely; rainfall, fog-drip, runoff, and evapotranspiration, as individual hydraulic boundaries. Normally, however, these features are not considered individually in a numerical model but are lumped together into a net recharge flux term. Therefore, recharge flux is more appropriately handled through a separate water-budget analysis which is covered later in this report.

Finally, there is the possibility that hydrostratigraphic boundaries, or multiple alternating layers of lava flows, have an effect on the isotropy and vertical flow of the model. The layered and alternating flank flow characteristics between a'a clinker zones and pahoehoe lava of the Hawaiian Islands, including Lana'i, would justify anisotropic conditions. There is evidence of perched conditions on Lana'i from two seeps upstream from the dry Waiapaa Tunnel (Stearns, 1940). These seeps were significant enough for drain basins to be built to collect and pipe the water to cattle. However, such seeps are considered localized features and given the regional scale of the model it is assumed that stratigraphy is more or less uniform at the larger scale. Therefore the island, as a whole, is assumed isotropic at the regional scale.

## Ground-Water Hydraulic Properties & Parameters

General ground-water hydraulic properties described herein are specific to the dynamics of the saturated portion of the aquifer alone. Necessary parameters for solutions in a numerical ground-water model are hydraulic conductivity, homogeneity, anisotropy, transmissivity, and the storage coefficient. Hydraulic conductivity is a proportionality constant based on both the fluid and the medium through which it passes and is essentially the capacity of a rock to transmit water. It is based on Darci's Law which is defined in Equation eq.(1).

$$Q = KA\left(\frac{dh}{dl}\right) \qquad \text{eq.(1)}$$

where:

$Q$ = quantity of water per unit of time ($L^3/t$)
$K$ = hydraulic conductivity (L/t)
$A$ = cross-sectional area perpendicular to flow ($L^2$)
$dh/dl$ = hydraulic gradient (dimensionless)

Hydraulic conductivity, ***K***, differs among different rock types but may also differ from place to place within the same rock. This characteristic refers to the *homogeneity* of the rock. If the ***K*** is the same throughout the rock then it is said to be *homogeneous*. If the ***K*** differs from one area to another it is said to be *heterogeneous*. In the real absolute world geology is always heterogenous. Although one can state that locally and in absolute terms that the ***K*** generally heterogenous, it was assumed that at the island scale the flank lava flows are homogenous while recognizing that these flows are cut by dikes and faulting of different ***K***s. Dikes are denser rock and it is well established that they have lower ***K***s than flank flows. Dike widths found in other dike complexes on Oahu range between 1 to 5 ft. thick although dike widths of 10 ft. or more are possible (Walker, 1987). However as stated earlier, they can be very numerous in a dike complex region. Additionally, extensive faulting on the island in the three major rift zones, as stated by Stearns (1940), more than likely act similar to dikes and should thus have low hydraulic conductivities. Like flank flows, it is assumed that at the regional island scale effective ***K***s for the network of dikes and faults in the rift zone are homogeneous although different than flank flows.

***K*** may also differ in different directions anywhere within a rock or an aquifer. This characteristic refers to the *isotropy* of the medium. If it is the same in all directions (x,y,z) it is said to be *isotropic*, if not then it is *anisotropic*. As stated earlier. the layered and alternating flank flow characteristics of the Hawaiian Islands lean towards anisotropic conditions. However, this is assumed to be insignificant at the regional island scale.

As a final note on ***K***, it is understood that the fluid in this study refers specifically to ground-water which is assumed to be uniform throughout the aquifer. Generally, ground-water in Hawaii is uniform in temperature and dissolved constituents. However, ground-water temperatures in and near the Palawai basin are significantly elevated and since temperature affects the kinematic viscosity of water it will affect the hydraulic conductivity in that area of the aquifer. Therefore, this phenomena should be kept in mind when reviewing results of the model. Additionally, the ground-water dissolved solids content in Palawai basin and near shore wells are elevated which change the density of the modelled fluid.

The range of ***K*** values for basaltic rock covers twelve (12) orders of magnitude (Heath, 1982). Thus, one can appreciate the variability involved with estimating effective ***K*** values in basaltic geology such as the Hawaiian Islands. Typical values for ***K*** for flank flows in Hawaii, based on pumpage tests, range from several thousands of feet per day in flank flows to a few feet per day (Sooros, 1973). ***K*** values for geologic features such as dikes are known to have low ***K*** values which have been reported as low $10^{-5}$ ft/day for massive igneous rocks (Todd, 1980).

Transmissivity, ***T***, is the product of hydraulic conductivity and the saturated thickness of an aquifer and is the capacity of an aquifer to transmit water. Transmissivity is defined in Equation eq.(2).

$$T = Kb \qquad \text{eq.(2)}$$

where:

$T$ = Transmissivity ($L^2/t$)
$K$ = Hydraulic Conductivity (L/t)
$b$ = Saturated thickness of aquifer (L)

Since ***T*** is dependent upon the saturated thickness, ***b***, of the aquifer and the fact that the Gyhben-Herzberg relationship (DuCommon, 1828; Ghyben, 1889; and Herzberg, 1901) exists in the Hawaiian islands, it must be understood that ***T*** is not constant but varies within Hawaiian aquifers. However, even without this assumption it is certain that the ***T*** on Lana'i is not constant. The fact that the water levels on Lana'i vary greatly identifies greatly varying values for ***b***. Since the bottom of the Lana'i ground-water aquifer has never been firmly established through well drilling and existing data it can only be assumed that the Gyhben-Herzberg relationship exists. If the Gyhben-Herzberg relationship does indeed exist then values for ***b***, thus ***T***, could range over several orders of magnitude.

Since ***T*** is dependent upon the value of ***K***, ***T*** is subject to the same concerns of homogeneity and isotropy as is ***K***. Again, these issues are assumed to have greater impact at the local scale rather than the regional scale of this model.

The storage coefficient, $S$, is the capacity of the aquifer to store water. $S$ is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area per unit change in head as follows in Equation eq.(3):

$$S = \frac{V_r}{A\,(\Delta h)} \qquad \text{eq.(3)}$$

where:

$S$ = Storage Coefficient (dimensionless)
$V_r$ = Volume of water released from aquifer ($L^3$)
$A$ = unit surface area ($L^2$)
$\Delta h$ = unit change in head level (L)

$S$ is most important in determining the transient response of an aquifer to stresses such as pumping. When steady-state conditions are investigated $S$ is set to zero (0) since transient behavior is not sought and water will be released from storage instantly. Once initial steady-state conditions are determined, i.e., initial water levels encountered are reasonably matched, then the $S$ can be determined through transient water level responses to pumping.

$S$ varies depending whether the aquifer is confined or unconfined. Ground-water released from storage in confined aquifers is predominantly from aquifer compression and the expansion of water under pressure. The reasonable range of $S$ for unconfined aquifers is 0.00001 to 0.001 (Heath, 1982). Ground-water released from storage in unconfined aquifers is predominantly from the gravity drainage through the geology when water levels decline and is essentially specific yield. The reasonable range of $S$ for unconfined aquifers is 0.1 to 0.3 (Heath, 1982). Additionally, for unconfined basal lens type aquifers water can also be released from bottom storage as the transition zone rises according to the Gyhben-Herzberg relationship and should affect $S$ by 41 times.

The common method of estimating the parameters described above are through aquifer pumping tests. Ideally, observation wells are used to observe aquifer water level drawdown responses to pumping wells. Such *multiple-well tests* are uncommon in Hawaii due to the additional costs involved. Typically, only the pumped well itself is the available source for aquifer test drawdown measurements. Such *single-well tests* introduce additional drawdown due to turbulent frictional forces as water leaves the aquifer and enters the well bore. Thus, most *single-well tests* have greater drawdown than that which occurs in the aquifer itself. This is a very *localized* source of error. Although this is one major source of error in estimating aquifer $K$, $T$, and $S$ values, there are many other *localized* sources of error associated with *single-well* aquifer pump tests. These sources of error and assumptions in aquifer pump testing are summarized as follows:

a. Aquifer is homogenous and isotropic.
b. Aquifer is infinite.
c. Position and nature of aquifer boundaries.
d. Occurrence and nature of confining beds.
e. Thickness of aquifer is known.
f. Fluid is homogeneous.
g. Flow to well is uniform and horizontal only.
h. Ideally, wells are fully, not partially, penetrating into the aquifer.
i. Length of aquifer pump test period is adequate.
j. Pumping rate is constant.
k. Well losses vs. aquifer losses are known.
l. Nominal vs. effective radius of well are known.

As stated earlier, one major assumption for this model is the regional scale the aquifer is homogeneous and isoptropic. This assumption is almost certainly invalid at the local scale associated with aquifer pumping tests. With these caveats in mind it is quite evident that effective ***K***, ***T***, and ***S*** values can only be approximated.

For Lana'i and in the well information portion of this report, Table 13, pg. 51, lists the results of field pumping test data which estimate the ***K***, ***T***, and ***S*** parameters. The average ***K*** of nine (9) tests is 18.3 ft/day, the average ***T*** of nine (9) pump tests is 7,854 $ft^2$/day, and ***S*** for based on one test is 0.1. These parameters are discussed in more detail in the well information section of this report.

## Water-budget Analysis

The goal of the water-budget analysis is to estimate how much water eventually reaches the ground-water table and becomes part of the ground-water system. This estimate is commonly known as ground-water recharge. What is not common is a universally accepted method for making this estimation (Anderson, & others, 1992). The general water-budget or mass-balance equation used to estimate recharge for this study was based on Equation eq.(4) as follows:

$$\boldsymbol{RF + FD + IR - DRO - \Delta SMS - ET = R} \quad \text{eq.(4)}$$

where:

***RF*** = Rainfall precipitation
***FD*** = Fog-drip precipitation
***IR*** = Irrigation return = 0 for this study.
***DRO*** = Direct runoff
**Δ*SMS*** = Change in soil-moisture storage
***ET*** = Evapotranspiration
***R*** = Recharge

In reality, Equation eq.(4) is the same equation used in all other previous studies for estimating Lanai's ground-water recharge, ***R***. In earlier studies for Lana'i the terms for fog-drip, ***FD***, irrigation, ***IR***, and soil-moisture storage, **Δ*SMS***, terms were not considered; in other words these parameters were set to zero (0). Later studies began to acknowledge the impact of ***FD*** on Lanai's ground-water ***R***. This study considers the effects of both ***FD*** and **Δ*SMS*** but continues to ignore ***IR*** effects.

Differences between estimations of ***R*** were thus based on hydrologists' differences in the values assigned individual parameters in Equation eq.(4). However, all the previous parameter estimations shared a significant commonality; parameter estimations were based on total annual averages. This study's parameter estimations are based on month-to-month variations to estimate annual averages.

The contemporary methodology, or Equation eq.(4), considers the difference between potential evapotranspiration, $ET_p$, vs. actual evapotranspiration, $ET_a$, in conjunction with **Δ*SMS***, considerations whereas previous water-budget analyses did not. Basically, this considers the available water for evaporation. The transient time periods selected could be monthly or even daily depending on the available data. Ultimately, using monthly averages for the given parameters while considering and including **Δ*SMS*** in the budget equation will result in a lower total annual value of $ET_a$. This is because at drier times of the year there is not enough soil-moisture available to achieve the full $ET_p$ which may otherwise be estimated at an evaporation pan station. This is especially true during periods of drought when soil-moisture is extremely low for short periods of time (State of Hawaii, 1991). Ostensibly, the contemporary approach typically yields greater ***R*** values than those derived solely by annual averages.

Other recent recharge analyses performed in Hawaii used monthly based averages for the water-budget parameters in conjunction with a transient $\Delta SMS$ parameter to arrive at a more accurate estimate of annual $R$ (Giambelluca, 1983, 1986 and Eyre, & others, 1986). For Lana'i, the monthly information for each parameter in Equation eq.(4), except $IR$, was entered and manipulated digitally with the Geographic Information System (GIS) ARC-INFO Version 6.0 (ESRI, 1992) to estimate the cell-by-cell mean monthly recharge values. This work was performed on a Data General AViiON 300 Series Workstation (Data General, 1990) in conjunction with a PRIME 9955 mini-computer (Prime, 1987). The geographic datum used in this study was based on the North American Datum of 1927 (NAD27).

The average month-to-month input values for all the parameters are straightforward historical data substitution except for $\Delta SMS$ which forces one to handle Equation eq.(4) in an iterative process. $\Delta SMS$ at each cell is calculated by using a month-to-month bookkeeping procedure. First, in the GIS water-budget model the difference between a month's total precipitation ($RF$ + $FD$) and direct runoff, $DRO$, at a given cell location represents the volume of water which infiltrates through the ground surface into the soil at that location for that month. This is shown mathematically in Equation eq.(5) as follows:

$$RF_m + FD_m - DRO_m = I_m \qquad \text{eq.(5)}$$

where:

$RF_m$ = Mean rainfall precipitation for month $m$

$FD_m$ = Mean fog-drip precipitation for month $m$

$DRO_m$ = Mean direct runoff for month $m$

$I_m$ = Mean infiltration, or water which passes into the soil, for month $m$

This infiltration, $I_m$, adds to the beginning or initial soil-moisture storage found at that cell location for that month. If the amount of $I_m$ plus the beginning soil-moisture storage, $(SMS_i)_m$, exceeds the maximum soil-moisture storage capacity, $SMS_{max}$, the excess drains through the cell and becomes the ground-water $R_m$ for the cell for that month. $SMS_{max}$ is equal to the available water in the soil which is the available water capacity (soil field capacity minus the wilting point) multiplied by the root zone depth of the vegetation. For each month this is represented mathematically in Equation eq.(5) as follows:

$$I_m + (SMS_i)_m - SMS_{max} = R_m \qquad \text{eq.(6)}$$

where:

$I_m$ = Mean infiltration for month $m$

$(SMS_i)_m$ = Initial soil-moisture storage at the beginning of month $m$

$SMS_{max}$ = Maximum soil-moisture storage capacity = (available water capacity) x (root zone depth)

$R_m$ = Mean recharge $\geq 0$, for month $m \geq 0$

Following this calculation, evapotranspiration, ***ET***, is then subtracted from the soil-moisture storage at the maximum monthly rate, $ET_p$, which is assumed to be the average amount of water which would evaporate from a properly operated Class A type pan (Ekern, & others, 1985), again, for that particular month. The justification for taking out ***ET*** after first calculating recharge is two-fold. First, ***R*** occurs mainly during storms, when ***RF*** intensity is high and ***ET*** is low. Secondly, the ***I*** rate through most soils is on the order of feet per day while ***ET*** rate is on the order of feet per year. Therefore, during and immediately after storms water can infiltrate through the ground surface and into the soil much faster than it can evaporate.

There are two different situations which affect estimating the $ET_a$ and ending soil-moisture storage, $(SMS_i)_{m+1}$, for each month's iteration. First, if $ET_p$ is greater than $SMS_{max}$ then the full $ET_p$ cannot be achieved. This means that $ET_a$ will be less than $ET_p$ since water stops evaporating once the soil-moisture reservoir is empty (see Figure 15, pg. 36). Therefore, $ET_a$ is equal to either $SMS_{max}$ or, if $SMS_{max}$ has not been reached, something less. The $(SMS_i)_{m+1}$ term would thus always be reset to zero (0) for the next monthly iteration. This first situation of estimating monthly $ET_a$ and $(SMS_i)_{m+1}$ is represented mathematically as follows:

If $(ET_p)_m > SMS_{max}$ then

$$(ET_a)_m = I_m + (SMS_i)_m - R_m \qquad \text{eq.(7)}$$

and

$$(SMS_i)_{m+1} = 0 \qquad \text{eq.(8)}$$

where:

$(ET_p)_m$ = Mean potential evapotranspiration for month $m$

$(ET_a)_m$ = Mean actual evapotranspiration for month $m$

$(I)_m$ = Mean infiltration for month $m$

$(SMS_i)_m$ = Initial soil-moisture storage at the beginning of month $m$

$R_m$ = Mean recharge for month $m \geq 0$, calculated from equation eq.(5), pg. 19

$(SMS_i)_{m+1}$ = Next month's initial soil-moisture storage

In the second situation, if $ET_p$ is less than $SMS_{max}$, or, if $SMS_{max}$ has not been reached, then the full $ET_p$ is achievable. In this case, $ET_a$ would equal $ET_p$. Also, the next month's $(SMS_i)_m$ would then be some residual amount left over after $ET_p$ has been removed from the soil-moisture reservoir. This second situation of estimating $(ET_a)_m$ and $(SMS_i)_{m+1}$ is represented mathematically as follows:

If $(ET_p)_m \leq SMS_{max}$ or $(ET_p)_m < I_m + (SMS_i)_m - R_m$ then

$$(ET_a)_m = (ET_p)_m \qquad \text{eq.(9)}$$

and

$$(SMS_i)_{m+1} = I_m + (SMS_i)_m - R_m - (ET_p)_m \qquad \text{eq.(10)}$$

where:

$(ET_p)_m$ = Mean potential evapotranspiration for month $m$
$(ET_a)_m$ = Mean actual evapotranspiration for month $m$
$I_m$ = Mean infiltration for month $m$
$(SMS_i)_m$ = Initial soil-moisture storage at the beginning of month $m$
$R_m$ = Mean recharge for month $m \geq 0$, calculated from equation eq.(5), pg. 19
$(SMS_i)_{m+1}$ = Next month's initial soil-moisture storage

Again, irrigation return, ***IR***, was not considered in this process for three reasons; 1) the irrigation fields were mostly outside the natural and most significant recharge area; 2) potable wells are generally outside and upgradient from the irrigated areas of pineapple; and 3) since pineapple production has ceased on the island the resulting recharge would be more indicative of present and near future recharge conditions. Ignoring ***IR*** water should be significant especially since studies have shown that pineapple reduces evapotranspiration to amounts that are only 20% of observed pan evaporation in the same area (Ekern, 1960). In other words, ***R*** should increase in areas where pineapple cultivation occurs.

In essence, this entire water-budget procedure combined with the GIS constitutes a model for recharge. Therefore, there are really two (2) separate models in this study; 1) the numerical ground-water flow model and 2) the recharge model. The results of the recharge model will be used as a part of the entire input to the numerical ground-water model.

Using equations eq.(4) through eq.(10) while ignoring ***IR***, the mean annual ***R*** can be calculated by summing resulting $R_m$ values for each grid cell. This annual value of ***R*** provides cell-by-cell ***R*** input for the ground-water flow model. This approach in updating ***R*** estimates is more rigorous and precise than any previous recharge work done for Lana'i. However, the true accuracy of this estimate, as with other water-budget methods, cannot be verified without a complete and long-term database of all parameters identified in equation eq.(4), pg. 18. Yet, this approach does provide a framework for and towards making more accurate future recharge estimations. Each parameter from the general Equation eq.(4), is now described in more detail for Lanai's specific situation.

## Rainfall Precipitation (*RF*)

Lana'i lies in the rain shadow of West Maui and East Molokai and, consequently, the island receives relatively little rainfall, ***RF***. Since 1914, a total of 52 rain gage stations have measured ***RF*** (Giambelluca, 1986, & Figure 9). There are currently eight (8) rain gage stations still in service which are tracked by the National Weather Service. Of these, only three (3) are read daily or hourly, the rest are read weekly. All these stations report total monthly rainfall, $RF_m$. The longest records of $RF_m$ come from rain gages at Lanai City, State Key No. 672, Figure 10, and Koele, State Key No. 693, Figure 11, which have a combined record of $RF_m$ from 1892 to the present. Lanai City has daily readings since 1930 and hourly readings since 1976 (Hydrosphere, 1992). The greatest hourly intensity on record is 2 in/hr on February 4, 1979 at SKN 672.

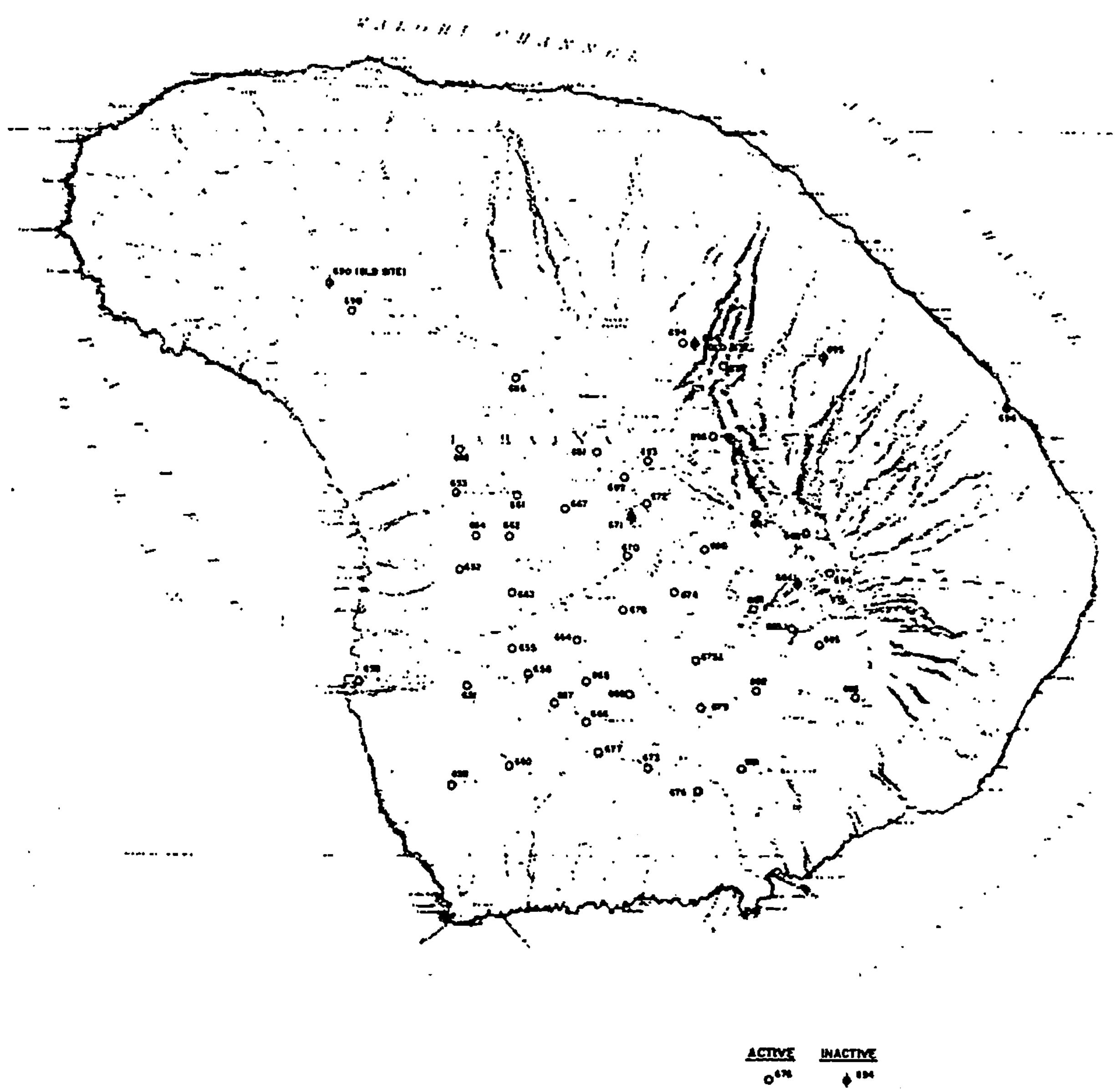



Figure 9. Rain Gage Locations for Lana'i (Giambelluca, & others, 1986)

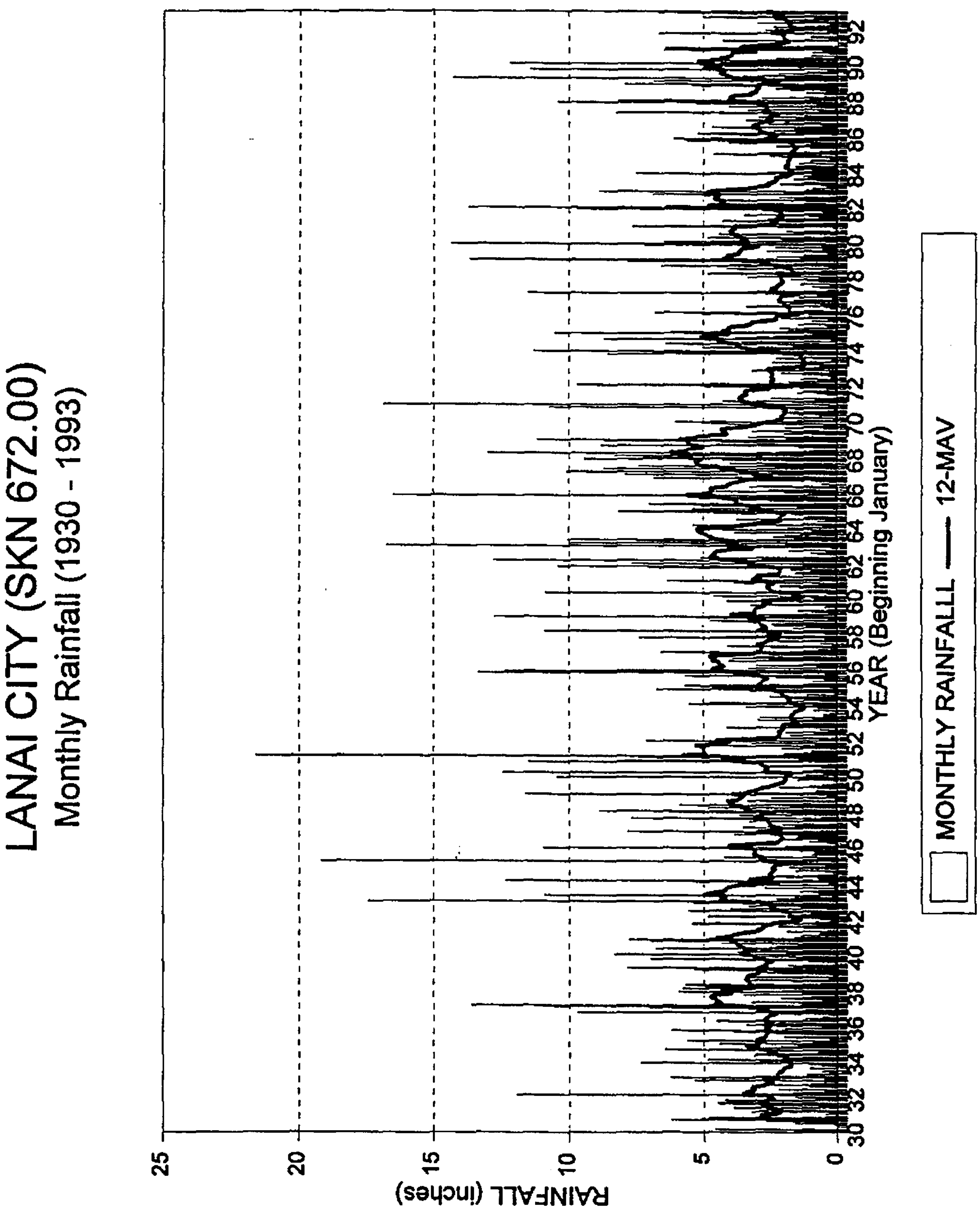
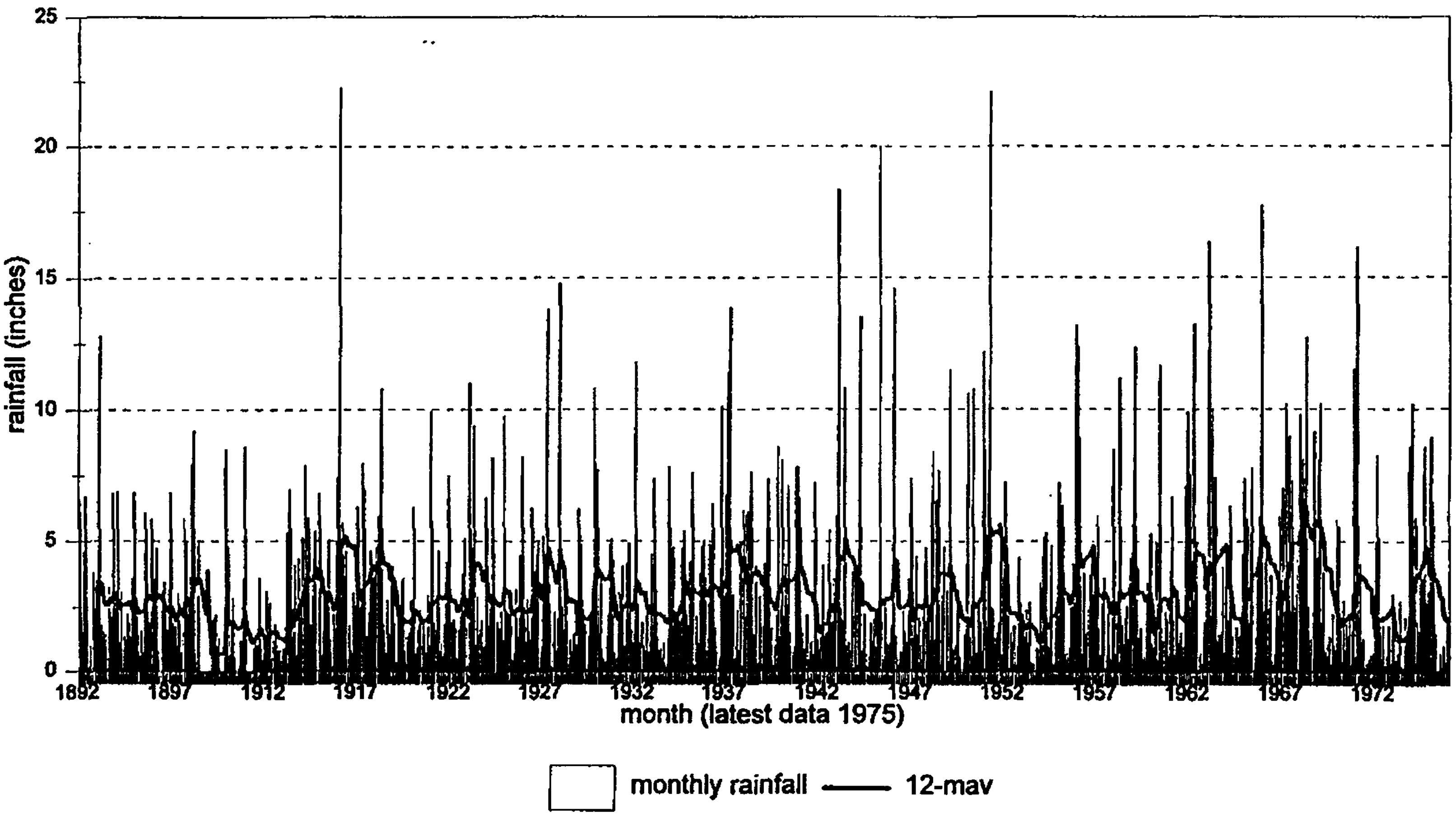



Figure 10. Monthly Rainfall at Lanai City State Key No. 672 (1930-1994)

Rainfall at Kolele, Lanai SKN 693.00
Monthly Rainfall 1892-1975



Hydrologists agree that the long-term annual average ***RF*** near the summit of the island is about 38 inches (CWRM, 1990). Annual average ***RF*** contribution to the water-budget in previous studies were determined by taking areal extents of and isohyetal information and producing total average annual volumes of ***RF***. In this study, mean (average) *monthly* isohyetal information was digitized from monthly figures in State Report R76 (Giambelluca, & others, 1986) and used in conjunction with the ARC-INFO GIS to estimate mean monthly rainfall for use in Equation eq.(4). The composite of monthly isohyetal information is graphically shown in Figure 12.

**TO BE UPDATED**

Figure 12. Composite of Monthly Rainfall Isohyets for Lana'i

## Fog-Drip Precipitation (*FD*)

Advective fog-drip, ***FD***, is a significant contributor to the water-budget analysis, not onl for Lana'i but for the other major islands as well (Stearns, & others 1942; Hawaii Water Author ity, 1959; Ekern, 1964, McKnight, & others, 1975, Juvik, & others, 1978). In its most basi description, ***FD*** is the condensation of fog or cloud water vapor on surface areas, such as leaves until such the surface area becomes saturated and water drips to the ground. ***FD*** productivity i dependant on water droplet size in the 3-100 μm range (McKnight, & others, 1975) and other fac tors such as humidity, temperature, forest canopy area, wind speed, etc. The phenomena is no unique to Hawaii as it has been studied in other areas of the world (Anon, 1954; Kerfoot, 1962 Kittredge, 1948; Marloth, 1905; Molchanov, 1960; Penman, 1963; Twomey, 1957, & Went 1955). Munro (1922) perhaps made the first direct observation of ***FD*** on Lana'i. Stearns (1946 identified ***FD*** as the source of ground water for Maui's Waikaukane Spring(s) during droughts For Lana'i, Stearns (1940) noted that in the central seven (7) square miles surrounding Lanaihal the soil is muddy or damp for most of the year. In support of this precipitation augmentation t rainfall are several reports which cite that the vegetation and soil type on Lanaihale are indicativ of a ***RF*** area greater than that measured. The State Land Study Bureau, LSB (Sahara, & other 1967) stated that the vegetation on or near Lanaihale is typical of a forest which exceeds an aver age annual ***RF*** of 60 inches and this apparent discrepancy with measured ***RF*** was attributed to th continuous cloud cover. SCS Soil maps of the island (Foote, 1972) identify the Kahanui-Kalae Kanepuu and the Amalu-Olokui soil associations in the proximity of Lanaihale which are indica tive of ***RF*** ranges of 30-50 inches/year and 75-150 inches/year, respectively and mention that th Kahanui Silty Clay Soil Series receives much of its moisture from ***FD***. Mink (1983) argued tha ***FD*** had to exist since the vegetation around Lanaihale was indicative of a forest with a ***RF*** rate o 65 inches/year or more. Hobdy (1993) identified a cloud and mesic forest community coverin the same approximate ***FD*** area for pre-polynesian conditions where, as he said, ***RF*** must hav ranged from 27-50 inches/year.

Direct observations of ***FD*** on Lana'i have been documented by Munro (1922 & 1929) Fosberg (1936), Carlson (1961), and Ekern (1964). Of these, the direct measurement of ***FD*** o Lana'i by Ekern is most significant. Based on three (3) continuous years worth of data, Eker (1964) found that cloud water interception (fog-drip) could increase annual precipitation below Norfolk Island Pine tree on Lana'i by as much as 30 inches/year. Ekern's study occurred betwee the summers of 1955 to 1958; a period covering a range of average ***RF*** (see Figure 10, pg. 23 which encompassed both a high and low in the 12-month moving average cycle. Also, his stud area was located in the middle of the ***FD*** region at an elevation (2,750 ft.) which is midwa between the base of the cloud cover (2,000 ft.) and the top of the island (3,370 ft.). Therefor Ekern's results should be a representative average for the ***FD*** region on Lana'i. Presently, Eker feels that the 30 inches/year figure is probably the upper limit of average ***FD*** contribution from Norfolk Pine to the water-budget for Lana'i (Ekern, personal communication, 4/19/1994). Ther is no compelling evidence that the climactic fog-drip potential, $FD_p$, for a similar Norfolk Pin has changed since Ekern's work and is considered the same today. However, McKnight (197 did design a computer program to differentiate between ***FD*** and non-vertical ***RF***, but wind data i required which was collected for only two (2) months during Ekern's study. However, it is impo tant to remember that the overriding factor for governing actual fog-drip, $FD_a$, is providing th medium upon which ***FD*** can condense and be harvested from the air. Therefore, changes in th type and density of the forest cover are more likely to change actual fog-drip on Lana'i tha changes in the surrounding ocean or global climate.

There has been theoretical laboratory experimentation for predicting fog-drip production, but this method it cannot be used due to the lack of appropriate Lana'i field data. Merriam (1973) proposed a method of predicting fog-water interception on leaves based on laboratory experimentation and also in earlier studies (1960 & 1961). He arrived at an exponential relationship but found that the there are a very large number of combinations of fog (cloud) water content, particulate matter, temperature, wind velocity, droplet size distribution, leaf surface area, leaf catching efficiency, and leaf storage capacities which would affect actual fog-drip and can vary rates by as much as 600%. These parameters have never been measured on Lana'i, or elsewhere for that matter, the method is simply impractical. This does not even consider the variability in vegetative areal distribution on Lana'i. Therefore, Ekern's field work study is more pertinent and was used in estimating ***FD*** contribution to Lanai's water-budget.

Two (2) estimates for ***FD*** were considered as potential input for the model. Both methods apply ***FD*** to areas above the base of normal cloud cover (2,000 ft.). The area encompassed by the 2,000 ft. contour is 8.36 square miles which is 17% more area than the year round damp area estimated by Stearns but is reasonably similar. The first method considered would be to use the reasonable maximum annual estimate for ***FD*** is 30 inches/year for the area above the 2,000 ft. elevation. Alternatively, a monthly ***FD*** to ***RF*** ratio (***FD/RF***) can be computed and used from Ekern's field work. Using the existing 3-year period of record of ***FD*** with the existing 82-years of monthly ***RF*** data, long-term monthly ***FD/RF*** ratios can be calculated. The resulting ratios can then be used to estimate values for monthly ***FD*** through the GIS model for ***R***.

It was decided that the monthly ***FD/RF*** ratio estimates were the more appropriate of the two methods for ***FD*** input. This is justified for four (4) reasons. First, this approach is more consistent with the overall monthly water-budget approach rather than using the 30 in/yr annual figure computed by Ekern (1964). Secondly, there is a long-term record of ***RF*** data to work with which provides a more solid basis for computing the ***FD/RF*** ratios. Thirdly, and as described earlier, the ***FD*** study was performed over a period of average ***RF***. Lastly, Ekern himself felt that the 30 in/yr figure was probably an upper limit rather than an average. The analysis and computation of monthly ***FD/RF*** ratios from Ekern's work is summarized in Table 2. Monthly ***FD*** and ***RF*** together equal total monthly precipitation.

Since ***FD*** is a significant contributor to the water-budget of Lana'i, the health of the forest canopy on Lanaihale is important. There have been concerns from Lana'i residents who have observed a significant decrease in the vegetation in the upper forest area. Historically, it is estimated that the native cloud, mesic, and dry forests once covered a much larger area than the present day forest (Hobdy, 1993). Hobdy identified four (4) major periods of forest reduction. The first began around 1400 A.D. when Hawaiian started moving to the island, with a peak population between 3000 to 3250 persons, and the undoubted forest clearing for farming and wood demand which ensued. In the 1800's goat, sheep, and hogs were introduced to the island whose combined population exceeded 50,000 in 1898 and had all but denuded the dry land forest and began to significantly impact the mesic and cloud forest cover. In the early 1900's the Gay family and, later, George C. Munro (LCo.) began and continued a goat, sheep, and hog eradication, upper forest fencing, and reforestation programs which resulted in a substantial recovery of the forest by 1927. Today, Axis Deer, introduced in the 1920's, are the present herbivore threat to the forests which has only been addressed recently, beginning around 1988, through increased hunting programs. Aerial photographic surveys done in 1954 and 1994 by the Division of Forestry and Wildlife, DLNR, are presently under examination for large scale changes in forest cover. However, this reconnaissance type of survey may not be able to determine the extent of changes forest undergrowth which is most vulnerable. by the feral herbivores.

## Table 2. Estimate of Monthly *FD/RF* Ratios

| Month[1] | *RF* Average Rainfall Collected in Open Area[1] (in.) | Average Precipitation Collected Under Pine[2] (in.) | Average Gain Under Pine (in.) | *FD* Average Fog Drip (0.375 x Gain)[3] (in.) | *FD/RF* Ratio |
|---|---|---|---|---|---|
| January | 3.47 | 9.18 | 5.70 | 2.14 | 0.62 |
| February | 3.12 | 14.12 | 10.99 | 4.12 | 1.32 |
| March | 4.62 | 7.14 | 2.52 | 0.95 | 0.21 |
| April | 2.43 | 5.82 | 3.39 | 1.27 | 0.52 |
| May | 8.42 | 17.19 | 8.77 | 3.29 | 0.39 |
| June | 7.10 | 18.54 | 11.44 | 4.29 | 0.60 |
| July | 4.30 | 12.14 | 7.85 | 2.94 | 0.68 |
| August | 3.24 | 10.04 | 6.80 | 2.55 | 0.79 |
| September | 4.80 | 10.18 | 5.28 | 1.98 | 0.41 |
| October | 3.96 | 7.31 | 3.36 | 1.26 | 0.32 |
| November | 3.09 | 11.47 | 8.38 | 3.14 | 1.02 |
| December | 1.31 | 7.31 | 6.00 | 2.25 | 1.72 |
| ANNUAL | 49.85 | 130.43 | 80.49 | 30.18 | *0.72 |

*(Source: Ekern, 1964.)*

NOTES:

FD/RF = Fog-drip to rainfall ratio.
1 = based on Ekern (1964) Table 1, 3-year period (7/55 to 6/58) of study. Average = Totals/ 3 years.
2 = 30-ft. Norfolk Pine.
3 = Ekern assumed that 50 inches of average annual gain (80 in.), or 62.5%, was captured rainfall.
na = Not applicable.
* = based on monthly ratios. If based on annual totals, *FD/RF* = 0.605.

The resulting annual ***FD/RF*** ratio of 0.72 is the average of the monthly ***FD/RF*** ratios ar compares well to ***FD*** studies which were performed after Ekern. Juvik (& others, 1978) used a updated fog-catchment device and a computer program (McKnight, & others, 1975) he helpe develop to isolate ***FD*** from non-vertical ***RF*** and arrived at a ***FD/RF*** ratio of 0.65 to 0.70 f Mauna Loa at the 2,500 meter (8,200 ft.) elevation. Obviously, with the studies performed on di ferent islands and elevations one would not expect identical results but they should be within tl same order of magnitude. The close agreement between the two studies suggests that Ekern's ea lier estimation of ***FD*** is not unreasonable although it may be an upper estimate. As such, tl results of Ekern's studies are considered the upper limit for ***FD*** contribution to ground-water ***R***.

## Irrigation Return (*IR*)

Although Lana'i pineapple covered up to 16,000 acres since 1923, irrigation return water, ***IR***, effects were ignored in this study for three reasons. First, the majority of the pineapple cultivation was located outside the area of primary ***R*** and ***FD*** and therefore does not have a significant impact in this critical area of the island. Secondly, large-scale pineapple irrigation occurred only over a short period of time from 1983 to 1991 when drip irrigation allowed an increased crop yields. Lastly, since large-scale pineapple production began to decline in 1992 and has almost ceased altogether on the island the resulting ***R*** would be more indicative of present and near-future recharge conditions.

While ignoring the ***IR*** component of the water-budget increases the conservative nature of the model, one cannot ignore that this approach does introduce a certain amount of uncertainty in ***R*** calculations. This would most affect water levels encountered in the proximity and downgradient of irrigation; namely Wells 1, 9, 10, 12, & 13, hence a certain amount of uncertainty in water levels encountered around the Palawai Basin, Wells 1, 9, & 10 and near Manele, Wells 12 & 13. However, most of these wells, with the exception of Well 1, were only drilled within the past seven (7) years. The pumping of upgradient wells since the 1950's has more than likely already affected water levels in these downgradient areas and probably introduces an equal, if not greater, uncertainty in the initial water levels encountered in these areas.

## Direct Runoff (*DRO*)

In general, total runoff is a combination of direct runoff, ***DRO***, which is the portion of ***RF*** water that flows immediately after rainfall, stream baseflow, or streamflow sustained by groundwater, or irrigation which flows overland and in stream or gulch channels to the ocean. ***DRO*** occurs only after interception, depression storage, and soil-infiltration rates are exceeded. This explains why in light rains there is little ***DRO***. Thus, it is during heavy rains when the majority of ***DRO*** occurs.

There is no streamflow or other ***DRO*** data for Lana'i which can be used to estimate this parameter accurately. Stearns (1940) stated that streams seldom flow except for kona storms and that Maunalei Gulch had been the only perennial stream on the island prior to its diversion from the tunnels. This description by Stearns is supplemented by the comments of Gay (1965) that the Maunalei flow in 1902 traveled a mile from its source at an estimated flow of 150,000 to 200,00 gallons per day. This would indicate that Maunalei was a losing stream before any major groundwater development occurred on the island although Gay also mentioned that 'old-timers' had said the stream used to flow to the sea year round. Currently, any overflow from the Maunalei Tunnels into the stream immediately infiltrates back into the ground and does not make it past Shaft 2 (McCullough, personal communication, 4/22/1995). Other previous estimations for ***DRO*** were made by simply assigning percentages of measured ***RF***. In this study, ***DRO*** was estimated by considering soil type characteristics as reported by the Soil Conservation Service (SCS) (Foote, & others, 1972; State of Hawaii, 1972). Drainability, permeability, slope, and runoff descriptions were the major soil characteristics considered in estimating ***DRO*** in relation to ***RF***. Lana'i soil data has been broken down into individual soil series and digitally compiled by the SCS on their GRASS GIS and imported to the USGS ARC-INFO GIS. The USGS GIS was used to compute individual cell monthly ***DRO*** values based on soil series characteristics in conjunction with ***RF*** trends. The GIS soil series data for Lana'i, as updated by SCS, is shown in Figure 13. Soil series parameters important to ***DRO*** estimation are shown in Table 3.

# TO BE UPDATED

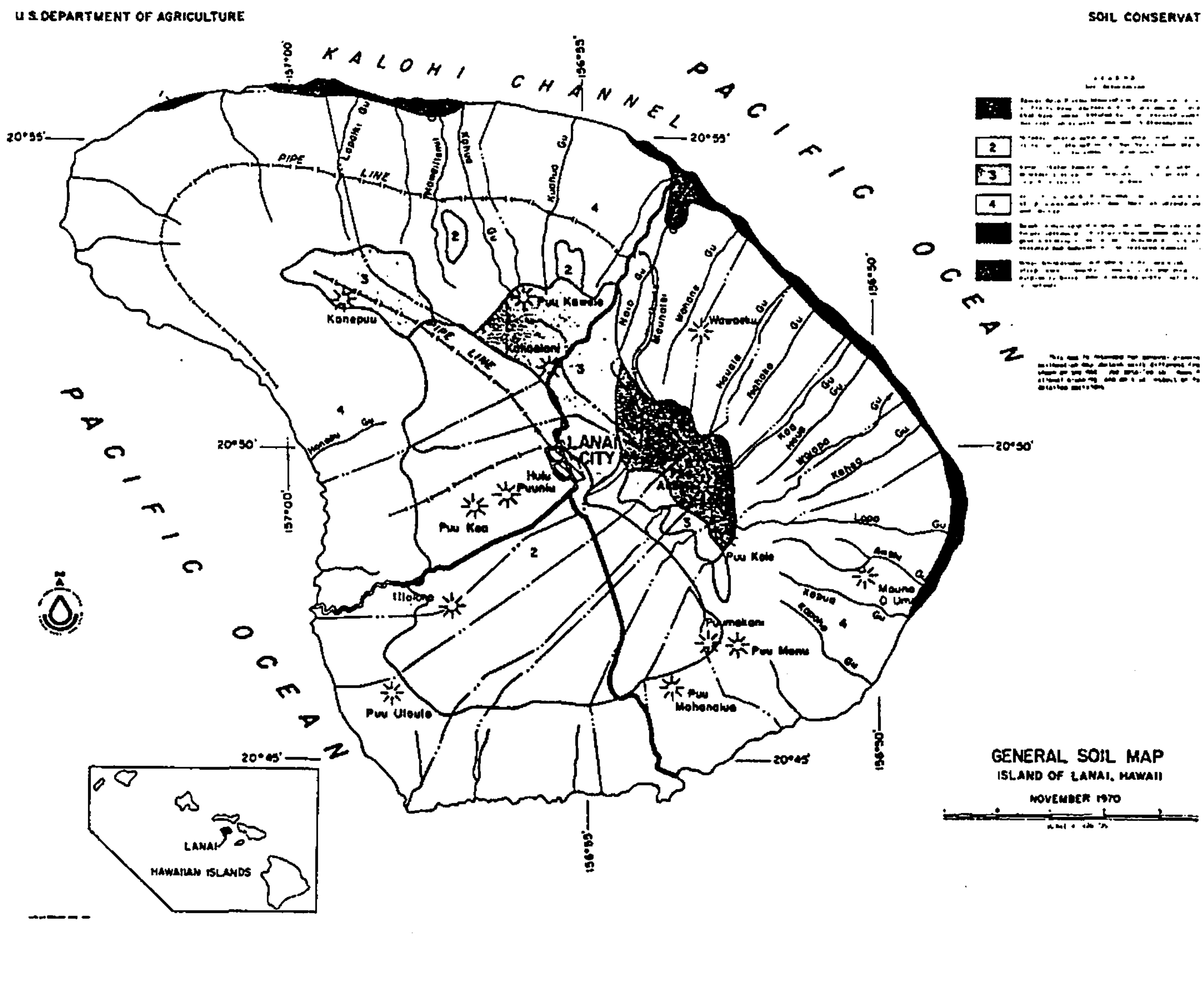



Figure 13. General Soil Map of Lana'i (based on Foote,& others 1972)

## Table 3. Lana'i Soil Characteristics for Runoff Estimation

| Soil Associations<br>*Soil Series* | Ranges | | | |
|---|---|---|---|---|
| | Drainability | Permeability (in/hr) | Slope (%) | Runoff[1] (description) |
| **Amalu-Olokui** | **Poorly to Well Drained** | **2.0 to 6.3** | **3 to extremely steep** | **Slow to rapid** |
| *Koele-Badland Complex* | *well drained* | *2.0 to 6.3* | *40 to 70* | *na* |
| *Koele Silty Clay Loam* | *well drained* | *2.0 to 6.3* | *3 to 25* | *slow to medium* |
| *Olokui Silty Clay Loam* | *poorly drained* | *2.0 to 6.3* | *3 to 30* | *slow* |
| *Rough Mountainous[2]* | *na* | *Permeable* | *extremely steep* | *rapid[3]* |
| **Jaucas-Mala-Pulehu** | **Well Drained** | **0.20 to 20.0** | **0 to 40** | **V. Slow to rapid** |
| *Beaches* | *na* | *na* | *na* | *na* |
| *Blown-out Land* | *na* | *na* | *0 to 40* | *rapid* |
| *Coral Outcrop* | *na* | *na* | *na* | *slow[3]* |
| *Jaucas Sand* | *excessively drained* | *6.3 to 20.0* | *0 to 15* | *very slow to slow* |
| *Mala Silty Clay* | *well drained* | *0.63 to 20.0* | *0 to 7* | *slow* |
| *Pamoa Silty Clay* | *well drained* | *0.20 to 0.63* | *5 to 20* | *medium* |
| *Pulehu Clay Loam* | *well drained* | *0.63 to 2.0* | *0 to 3* | *slow* |
| *Pulehu Sandy Loam* | *well drained* | *0.63 to 2.0* | *2 to 6* | *slow* |
| *Pulehu Stony Sandy Loam* | *well drained* | *0.63 to 2.0* | *0 to 7* | *slow* |
| *Sandy Alluvial Land* | *na* | *na* | *0 to 5* | *slow[3]* |
| **Kahanui-Kalae-Kanepuu** | **Well Drained** | **0.63 to 6.3** | **2 to 25** | **Slow to rapid** |
| *Kahanui Silty Clay* | *well/moderately drained* | *2.0 to 6.3* | *3 to 20* | *na* |
| *Kalae Silty Clay* | *well drained* | *2.0 to 6.3* | *2 to 25* | *slow to rapid* |
| *Kanepuu Silty Clay* | *well drained* | *0.63 to 2.0* | *3 to 15* | *slow to rapid* |
| *Pooku Silty Clay Loam* | *well drained* | *2.0 to 6.3* | *8 to 25* | *slow to medium* |
| **Molokai-Lahaina** | **Well Drained** | **0.06 to 2.0** | **0 to 40** | **Slow to rapid** |
| *Lahaina Silty Clay* | *well drained* | *0.63 to 2.00* | *0 to 40* | *slow to medium* |
| *Lualualei Clay* | *well drained* | *0.06 to 0.20* | *0 to 2* | *slow* |
| *Molokai Silty Clay Loam* | *well drained* | *0.63 to 2.00* | *3 to 15* | *medium to rapid* |
| *Uwala Silty Clay Loam* | *well drained* | *0.63 to 2.00* | *2 to 15* | *slow to medium* |
| *Waihuna Clay* | *well/moderately drained* | *0.20 to 0.63* | *0 to 25* | *slow to medium* |
| *Waihuna Gravelly Clay* | *well/moderately drained* | *0.20 to 0.63* | *3 to 7* | *slow* |
| *Waikapu Silty Clay Loam* | *well drained* | *0.63 to 2.0* | *0 to 15* | *slow* |
| **Very Stony-Rock Land** | **na** | **na** | **0 to precipitous** | **M. slow to v. rapid** |
| *Riverwash* | *na* | *na* | *na* | *na* |
| *Rock Land* | *na* | *na* | *level to very steep* | *very rapid[3]* |
| *Rock Outcrop* | *na* | *na* | *gentle to precipitous* | *very rapid[3]* |
| *Rough Broken Land* | *na* | *na* | *40 to 70* | *rapid* |
| *Stony Alluvial Land* | *na* | *na* | *0 to 5* | *moderately slow* |
| *Stony Blown-Out Land* | *na* | *na* | *7 to 30* | *rapid* |
| *Very Stony Land* | *na* | *na* | *7 to 30* | *moderately rapid* |
| *Very Stony Land Eroded* | *na* | *na* | *3 to 40* | *moderately rapid* |

*(Source: Foote, & others, 1972 & State of Hawaii, Report R44, 1972.)*

**NOTES:**

na = Not available

1 = runoff is based on permeability and slope of soil.

2 = soil mantle is very thin; 1 to 10 inches over saprolite. Saprolite is soft and permeable to water & roots.

3 = SCS data based on Smith, 10/20/94.

It is important to understand the degree with which the soils characteristics are known. The soil associations shown in Figure 13 and Table 3 are general mapping units of soil in which there is considerable uniformity in the pattern and extent of relative soils. However, individu *soil series* may differ greatly from one to another within the association and may even cross se eral associations. The hierarchy of soil types broken down by the SCS mapping effort is as fo lows: Associations, Series, and Phases. High- and medium-intensity surveys were done c cultivated areas, low-intensity surveys were made on grazing and forested land, and aerial reco naissance-surveys were made in inaccessible areas. Therefore, on Lana'i, the extent of soils i the Molokai-Lahaina association are better known than the Kahanui-Kalae-Kanepuu, Amal Olokui, and Rock Land Associations.

In light of the limited ***DRO*** information, Table 4 is a summary of the approach used in th study to quantify ***DRO***.

## Table 4. *DRO/RF* Ratios from Pearl Harbor for Lana'i

| Pearl Harbor, Oahu | | | | | Similar soil series exist on Lana'i? |
|---|---|---|---|---|---|
| *Soil Series (slope)* at least 80% in a mesh element | Elements matching criteria[1] | Average Annual of Elements | | | |
| | | *RF*[2] (in.) | *DRO*[3] (in.) | *DRO/RF* Ratio | |
| *FL - Fill Land, Mixed (na)* | 1 | 32.98 | 4.31 | 0.13 | No |
| *HLMG- Helemano Silty Clay (30-90%)* | 2 | 70.34 | 8.13 | 0.12 | No |
| *KyA - Kunia Silty Clay (0 - 3%)* | 0 | *na* | *na* | *na* | No |
| *LaB - Lahaina Silty Clay (3 - 7%)* | 2 | 44.02 | 4.16 | 0.09 | Yes |
| *LeB - Leilehua Silty Clay (2 - 6%)* | 0 | *na* | *na* | *na* | No |
| *MuB - Molokai Silty Loam (3 - 7%)* | 4 | 38.24 | 2.32 | 0.06 | Yes |
| *MuC - Molokai Silty Loam (7 - 15%)* | 0 | *na* | *na* | *na* | Yes |
| *rRK - Rock Land (level to very steep)* | 8 | 41.66 | 5.03 | 0.12 | Yes |
| *rRT-Rough Mountainous Land (very steep)* | 0 | *na* | *na* | *na* | Yes |
| *rTP-Tropohumults-Dystrandepts(30-90%)* | 15 | 41.54 | 4.73 | 0.11 | No |
| *WaA - Wahiawa silty clay (0 - 3%)* | 0 | *na* | *na* | *na* | Yes |
| *WzA - Waipahu silty clay (0 - 2%)* | 0 | *na* | *na* | *na* | No |

*(Sources: Foote, & others, 1972; State of Hawaii, Report R44, 1972; & Giambelluca, & others, 1983 &1986.)*

**NOTES:**

*na* = Not available or applicable.

1 - number of element matches where 80%,or more, of the same soil type dominates in an finite-element cell for the Pearl Harbor RASA model, average annual rainfall ≈ 30"/yr, and topography approximates conditions on Lana'i.

2 - *RF* = Rainfall from Giambelluca (& others, 1986).

3 - *DRO* = Direct Runoff from Giambelluca (1983 & 1986).

Previous ***DRO*** estimation methodology for ***R*** analysis by Giambelluca (1983 & 1986) was considered for this study since no other measured ***DRO*** data is available for Lana'i. Giambelluca used soil series information in conjunction with SCS runoff curves to arrive at ***DRO*** values for specific soil series in the Pearl Harbor, Oahu region. Results for Pearl Harbor ***DRO*** using this method can then be compared to corresponding ***RF*** to estimate direct runoff/rainfall ratios, or ***DRO/RF***. The ***DRO/RF*** ratio is simply the percentage of ***RF*** which becomes ***DRO***. Therefore, if comparable soil series can be found between the Pearl Harbor study area and Lana'i, then ***DRO/RF*** ratios can be used estimate ***DRO*** as a percentage of the historical ***RF*** record available on Lana'i. ***DRO*** computations were done for the USGS's recently approved RASA model element mesh for Pearl Harbor. The results were reviewed with the aid of GIS to find similar conditions which exist on both islands. Table 4 summarizes the search results for dominant soil series in the RASA model's element mesh and how they relate to Lana'i.

Table 4 lists the soil series which occupied 80% or more of an element in the Pearl Harbor RASA mesh. There were 177 elements in the mesh which met this initial criteria. These elements were then checked for ***RF*** (≈ 30"/yr) and topographical (slope) conditions similar to Lanai. This resulted in a match for fourteen (14) elements among three (3) similar soil series between the two islands. Admittedly, this is a small number of soil series matches considering that there are over fifty-eight (58) individual soil series on Lana'i, but this approach considers the most contemporary estimation method for ***DRO*** in lieu of any corresponding data for Lana'i.

The three (3) ***DRO/RF*** ratios highlighted in Table 4 identify what is believed to be reasonable values for slow, medium, and rapid ***DRO*** for Lana'i. As can be seen on Table 3, pg. 31, SCS describes ***DRO*** for individual soil series *qualitatively* in categories of slow, medium, rapid, and very rapid according to soil permeability and slope. Slopes of the three similar soils, from Table 4, in their corresponding Pearl Harbor mesh element location were determined manually from UGGS quadrangle maps. The Molokai silty loam (*MuB*) elements identified in the Pearl Harbor model had typical slopes of 5% which is in the middle of the slope range described by SCS for this soil series. Similarly, the Lahaina silty clay (*LaB*) and rock land (*rRK*) elements had slopes of approximately 8%and 14%, respectively, which put them into the upper slope ranges in their soil series as described by SCS. Soil series for Lana'i can be grouped according to slope and the *qualitative* ***DRO*** description assigned by SCS. The only exception to the SCS descriptions were for *LaB* since its slope in Pearl Harbor approximated 8%. Given this arrangement, it is found that the highlighted ***DRO/RF*** ratio results from Table 4 can be used to estimate Lana'i soil ***DRO*** characteristics of similar SCS slope and *qualitative* ***DRO*** descriptions. This approach is summarized in Table 5 and constitutes the justification for use of ***DRO/RF*** ratios in the GIS analysis.

As a final check, one can compare the the greatest hourly intensity of rainfall on record (2 in/hr) against the permeability rates, slope, and runoff description of soils in Table 3, pg. 31. From this comparison it is evident that the Molokai-Lahaina soil associations and series are the soils which probably produce the majority of ***DRO*** in conjunction with very steep areas. For the rest of the island there are few large events which exceed the permeability rates of the soils listed. Thus, it is reasonable to assume small percentages of ***DRO*** occur compared to the total ***RF*** measured on Lana'i. In fact, the topography of the island is indicative of limited ***DRO***. On the leeward side of Lana'i there are no valleys and only a few small gulches. On the windward side of Lana'i there exists numerous large gulches but no valleys.

## Table 5. Final *DRO/RF* Ratios for Lana'i

| *DRO* / *RF* Ratio | 0.06 | | 0.09 | 0.12 | |
|---|---|---|---|---|---|
| Runoff@ | Slow | | Medium | Rapid | |
| Slope@ | 0 - 3% | >3 - 7% | >7 - 15% | >15 - 25% | 25 - 70% |
| Soil Series | Bs | KcB | Bw | KcD3 | LaE3 |
| | CR# | KhB | KcC | KrD | rRO# |
| | JaC | KhB2 | KhC | LaD3 | rRR# |
| | KASD | KrB | KhC2 | MvD3 | rRT# |
| | LaA | LaB3 | KrC | rRK# | |
| | LuA | MmB | KRL | rSN# | |
| | MmA | MuB | LaB | WoD | |
| | MuA | PoaB | LaB3 | | |
| | OOE | UwB | LaC | | |
| | PoB | WoB | LaC3 | | |
| | PsA | WohB | MuC | | |
| | rSL# | | MuC3 | | |
| | WoA | | NAC | | |
| | WrA | | PID | | |
| | | | PID2 | | |
| | | | rSM# | | |
| | | | rVS# | | |
| | | | rVT2# | | |
| | | | UwC | | |
| | | | UwC3 | | |
| | | | WoC | | |
| | | | WrC3 | | |

**NOTES:**

@ = SCS data (Foote, & others, 1972 & State of Hawaii, R44, 1972)

# = SCS data based on Smith, 10/20/94)

As as final note, the ***DRO*** which gathers in topographical depressions and has an add chance for infiltration is ignored in the GIS recharge model. Island-wide this may be insignific but in the Palawai area the affect on recharge could be significantly in error.

## Changes in Soil-Moisture Storage ($\Delta SMS$ & $SMS_{max}$)

With equation eq.(5), pg. 19, and ***RF***, ***FD***, ***DRO***, and ***I*** defined, we can now discuss soil-moisture in detail. It is helpful to refer to Figure 14, an idealized cell diagram, when discussing soil-moisture storage and changes in soil-moisture storage. Additionally, Figure 14 is good for visualizing the computation of monthly mean recharge, $R_m$.

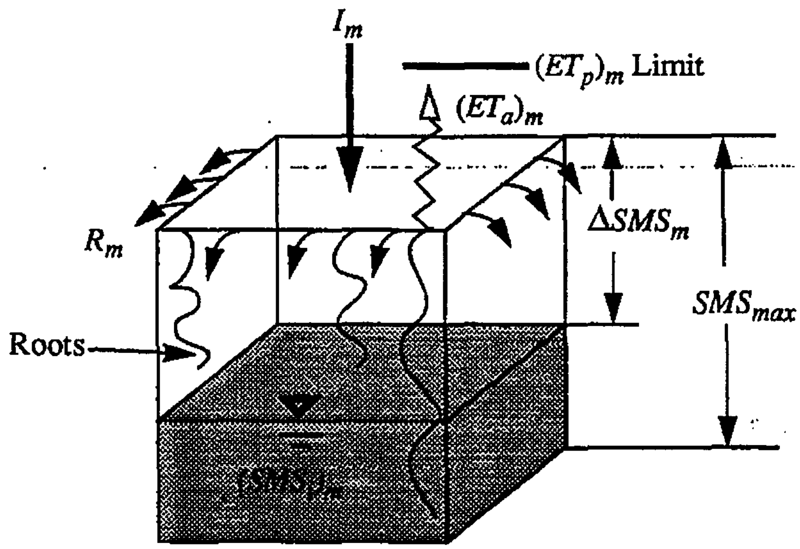



Figure 14. Soil-Moisture Storage Cell Diagram

where:

$I_m$ = Mean infiltration for month $m$

$(SMS_i)_m$ = Initial soil-moisture storage at the beginning of month $m$

$SMS_{max}$ = Maximum soil-moisture storage capacity = (available water capacity) x (root zone depth)

$R_m$ = Mean recharge for month $m \geq 0$, calculated from equation eq.(5), pg. 19

$(SMS_i)_{m+1}$ = Next month's initial soil-moisture storage

$(ET_p)_m$ = Mean potential evapotranspiration for month $m$

$(ET_a)_m$ = Mean actual evapotranspiration for month $m$

It is important to understand that Figure 14 is a simplified cell diagram which represen how soil-storage is computed. $SMS_{max}$ is the maximum volume of water which remains the soil root zone after it is drained and capillary forces between water and the soil cannot be overcome t gravity. Drainage, which is really $R$, actually takes place at the bottom of the soil layer rather th overflowing the top as is shown in the cell diagram. However, the computation is equivalent.

The domain of $SMS_{max}$ is defined by the depths of the deepest roots in a soil series and equal to the available water capacity (soil field capacity minus the wilting point) multiplied by tl root zone depth of the vegetation. Field capacity is analogous to specific retention or the wat which remains in the soil after it is drained. The wilting point is the pore pressure limit whi plants cannot overcome to further transpire, or use, water; hence they wilt. The root zone depth defined as the deepest roots in the soil series where the SCS descriptions changed from any ty of roots mentioned to "no roots" or if no reference to any roots occurred. This domain of $SMS_m$ was assumed constant throughout the soil series without any consideration given to actual veget tive cover which probably differed spatially on all soil series. This assumption may or may not l conservative depending on the representativeness of the SCS soil description. Soil depth, max mum root zone depth, and available water capacity were reviewed in estimating $SMS_{max}$ for a soil series. SCS information concerning these parameters for soils on Lana'i are summarized Table 6 and soil coverages for the water-budget analysis were used from those digitized by SCS

The monthly change in soil-moisture storage, or $\Delta SMS_m$, is the additional volume water necessary to fill the soil up to its $SMS_{max}$. Obviously, the magnitude of $\Delta SMS_m$ is depe dent upon the magnitude $SMS_{max}$. Its domain is limited by and coincident with $SMS_{max}$ but va ies with time.

With $SMS_{max}$ and $\Delta SMS_m$ defined, the process describing the remaining parameters Figure 14 is straight forward. For a given month $m$ there is a beginning soil-moisture stora value, $(SMS_i)_m$. Any average monthly infiltration water, $I_m$, which exceeds $\Delta SMS$ also excee $SMS_{max}$ and goes towards that month's recharge, $R_m$. The remaining volume of water in the c after this initial process is then decreased via and up to that month's average $ET_p$, or $(ET_p)_m$, a the $(SMS_i)_m$ value for the next month, $(SMS_i)_{m+1}$, is the water remaining in the soil, if any. $(ET_p)_m$ is greater $SMS_{max}$ than $(SMS_i)_{m+1} = 0$.

## Table 6. Soil Characteristics for $\Delta SMS_{max}$ Estimation

| Soil Associations *Soil Series* | Ranges | | |
|---|---|---|---|
| | Soil Depth (in.) | Maximum Root Zone Depth@ (in.) | Available Water Capacity (in/in of soil) |
| **Amalu-Olokui** | **0 to 60** | **11 to 20** | **0.12 to 0.15** |
| *Koele-Badland Complex* | *0 to 55* | *18* | *0.12 to 0.14* |
| *Koele Silty Clay Loam* | *0 to 55* | *18* | *0.12 to 0.15* |
| *Olokui Silty Clay Loam* | *0 to 60* | *11* | *0.12 to 0.14* |
| *Rough Mountainous*[2] | *0 to 10* | *6 to 20*[3] | *na* |
| **Jaucas-Mala-Pulehu** | **0 to 62** | **0 to > 60** | **0.05 to 0.13** |
| *Beaches* | *na* | *0$* | *0.03 to 0.05* |
| *Blown-out Land* | *na* | *1$* | *0.03 to 0.05* |
| *Coral Outcrop* | *na* | *1$* | *0.04%* |
| *Jaucas Sand* | *0 to 60* | *22* | *0.05 to 0.07* |
| *Mala Silty Clay* | *0 to 40* | *40* | *0.06 to 0.13* |
| *Pamoa Silty Clay* | *0 to 62* | *62* | *0.09 to 0.11* |
| *Pulehu Clay Loam* | *0 to 60* | *60* | *0.09 to 0.13* |
| *Pulehu Sandy Loam* | *0 to 60* | *60* | *0.09 to 0.13* |
| *Pulehu Stony Sandy Loam* | *0 to 60* | *60* | *0.09 to 0.13* |
| *Sandy Alluvial Land* | *na* | *>60$* | *0.03 to 0.04* |
| **Kahanui-Kalae-Kanepuu** | **0 to 67** | **53 to 62** | **0.10 to 0.14** |
| *Kahanui Silty Clay* | *0 to 60* | *60* | *0.10 to 0.12* |
| *Kalae Silty Clay* | *0 to 67* | *53* | *0.12 to 0.14* |
| *Kanepuu Silty Clay* | *0 to 61* | *61* | *0.11 to 0.13* |
| *Pooku Silty Clay Loam* | *0 to 62* | *62* | *na* |
| **Molokai-Lahaina** | **0 to 72** | **15 to 60** | **0.09 to 0.14** |
| *Lahaina Silty Clay* | *0 to 60* | *46* | *0.10 to 0.13* |
| *Lualualei Clay* | *0 to 60* | *60* | *0.11 to 0.13* |
| *Molokai Silty Clay Loam* | *0 to 72* | *15* | *0.11 to 0.13* |
| *Uwala Silty Clay Loam* | *0 to 60* | *26* | *0.10 to 0.12* |
| *Waihuna Clay* | *0 to 65* | *18* | *0.09 to 0.11* |
| *Waihuna Gravelly Clay* | *0 to 65* | *18* | *0.09 to 0.11* |
| *Waikapu Silty Clay Loam* | *0 to 60* | *24* | *0.12 to 0.14* |
| **Very Stony-Rock Land** | **na** | **4 to 80** | **na** |
| *Rock Land* | *Shallow* | *55% @ 4 to 10#* | *0.12 to 0.16* |
| *Rock Outcrop* | *Exposed bedrock* | *10% @ 4 to 8#* | *na* |
| *Rough Broken Land* | *< 20* | *90% @ 40 to 80#* | *0.14 to 0.16* |
| *Stony Alluvial Land* | *na* | *>60#* | *0.05 to 0.07* |
| *Stony Blown-Out Land* | *na* | *20% @ 2 to 10#* | *0.07 to 0.09* |
| *Very Stony Land* | *Little soil* | *75% @ 4 to 20#* | *0.08 to 0.10* |
| *Very Stony Land Eroded* | *na* | *80% @ 10 to 20#* | *0.08 to 0.10* |

*(Source: Foote, & others, 1972 & State of Hawaii, Report R44, 1972.)*

**NOTES:**

$ET_p$ = Potential evapotranspiration
na = Not available
@ = Depth to top of profile identified as having 'no roots'.
# = SCS data based on Smith, 10/20/94.
$ = Assumed
% = SCS data based on Smith, written personal communication, 10/20/94

As can be seen in Table 3, the ranges for the parameters important in estimating $SMS_{ma}$ are great. Ultimately, maximum root zone depths and average available water capacity were usec for each soil series in the calculating $SMS_{max}$. For those available water capacities with no infor mation reasonable values were assumed. The final GIS input values for individual soil series ar summarized in Table 7 below.

**Table 7. Final Parameters for Lana'i $\Delta SMS_{max}$ Estimation**

| *Soil Series* | Maximum Root Zone Depth (in.) | Available Water Capacity (in/in of soil) | *Soil Series* | Maximum Root Zone Depth (in.) | Available Water Capacity (in/in of soil) | *Soil Series* | Maximum Root Zone Depth (in.) | Availab Water Capaci (in/in of s |
|---|---|---|---|---|---|---|---|---|
| *BS* | 0 | 0.04 | *LaC* | 46 | 0.11 | *rRR* | [a]54 | [b]0. |
| *BW* | 1 | 0.12 | *LaC3* | 46 | 0.11 | *rRT* | [a]12 | [b]0. |
| *CR* | 1 | [b]0.04 | *LaD3* | 46 | 0.11 | *rSL* | [a]50 | [b]0. |
| *JaC* | 22 | 0.06 | *LaE3* | 46 | 0.11 | *rSM* | [a]50 | [b]0. |
| *KASD* | 60 | 0.11 | *LuA* | 60 | 0.12 | *rSN* | [a]1 | [b]0. |
| *KRL* | 18 | 0.14 | *MmA* | 40 | 0.12 | *rVS* | [a]9 | [b]0. |
| *KcB* | 53 | 0.13 | *MmB* | 40 | 0.12 | *rVT2* | [a]12 | [b]0. |
| *KcC* | 53 | 0.13 | *MuA* | 15 | 0.12 | *rRO* | [a]0.60 | [b]0. |
| *KcD3* | 53 | 0.13 | *MuB* | 15 | 0.12 | *UwB* | 26 | 0. |
| *KhB* | 61 | 0.12 | *MuC* | 15 | 0.12 | *UwC* | 26 | 0. |
| *KhB2* | 61 | 0.12 | *MuC3* | 15 | 0.12 | *UwC3* | 26 | 0 |
| *KhC2* | 61 | 0.12 | *MuD3* | 15 | 0.12 | *WoA* | 18 | 0 |
| *KrB* | 18 | 0.14 | *NAC* | 52 | 0.10 | *WoB* | 18 | 0 |
| *KrC* | 18 | 0.14 | *OOE* | 11 | 0.25 | *WoC* | 18 | 0 |
| *KrD* | 18 | 0.14 | *PID* | 62 | 0.10 | *WoD* | 18 | 0 |
| *LaA* | 46 | 0.11 | *PID2* | 62 | 0.08 | *WohB* | 18 | 0 |
| *LaB* | 46 | 0.11 | *PoB* | 60 | 0.12 | *WrA* | 24 | 0 |
| *LaB3* | 46 | 0.11 | *PoaB* | 60 | 0.09 | *WrC3* | 24 | 0 |
| | | | *PsA* | 60 | 0.14 | | | |
| | | | *rRk* | [a]4 | [b]0.14 | | | |

a. SCS data based on Smith, 10/20/94

b. based on Simmons, N. (10/11/94) and Nakamura. S. (12/1/94) written personal communication.

*(Source: Foote, & others, 1972 & State of Hawaii, Report R44, 1972.)*

## Evapotranspiration ($ET, ET_p, \& ET_a$)

Evapotranspiration, ***ET***, is the combination of evaporation and plant transpiration processes which return water to the atmosphere. It is important to understand that these two processes are very difficult to segregate (Todd, 1980). in this study, potential ***ET***, or $ET_p$, is very is assumed to be the water which will evaporate from a properly operated Class A type pan. This, in turn, identifies maximum $ET_p$. It is also important to understand that many factors affect pan evaporation, such as temperature, humidity, solar radiation, wind, and even the height of the pan above the ground, but all these data are not available for Lana'i. It is important to note that the error associated estimating evaporation from a Class A pan itself can be as much as ± 10% (Ekern, & others, 1985, Shuttleworth, 1993). Aside from pan evaporation methods, hydrologists commonly use the Penman Equation (Penman, 1948) to estimate the potential for evaporation from the surface of water, exposed openly to the air, through aerodynamic and energy budget considerations. Chang (1968) noted that the Penman Equation only gives approximations of open water evaporation and is also different than $ET_p$ where vegetation type and height is important. The same factors which affect $ET_p$ also affect actual ***ET***, or $ET_a$, but the influence of vegetative type and density, root-zone depth, soil-moisture storage (***SMS***), and density of capillary tubes in the soil are additional considerations. $ET_a$ can be estimated as percentages of $ET_p$. Normally, increases in all factors result in increased $ET_a$ although it has been shown that some vegetative cover can actually reduce $ET_a$ such that it is significantly less than $ET_p$. Pineapple has been shown to reduce local $ET_a$ by about 20% below $ET_p$ (Ekern, 1960). However, $ET_a$ can also exceed measured pan evaporation, $ET_p$. In optimum sugarcane cultivation conditions, sugarcane water requirements may go as high as factors of 1.1 to 1.2 times pan evaporation (Chang, 1961; Jones, 1980).

There is little direct pan evaporation data to estimate $ET_p$ on Lana'i. State Report R74 (Ekern, & others, 1985) identifies only one pan evaporation station, Station No. 687.00 at Lana'i City, having a limited duration of data collection (1957-1958) with an average rate of 25.63 in./yr. This measured amount is quite low, especially knowing that over the open ocean the pan evaporation rate is approximately 80 in./yr. The lower temperature associated with the higher elevation of Lanai City (>1500 ft. msl) is probably a major reason for this lower measurement. According to LCo. there is no additional data they have on file. Stearns (1940) stated that it is obvious that transpiration requirements are not met on Lana'i except for the seven (7) square miles around Lanaihale where the soil is muddy or damp for most of the year. Ostensibly, earlier overall ***ET*** estimates were based on professional opinion.

Although pan evaporation data is limited, three (3) methods were considered to estimate $ET_p$ patterns. In both methods, it is assumed that $ET_p$ is equal to pan evaporation. First, one could use Ekern's (& others, 1985) state-wide pan evaporation study conclusion that in areas beneath tradewind orographic clouds evaporation ranges from 30 to 40% less than the oceanic rate while in dry leeward areas evaporation was 30 to 40% more than the oceanic rate. These rates could then be applied uniformly for areas above and below the 2000 ft. elevation, respectively. Secondly, monthly $ET_p/RF$ rations could be estimated and used in spatially consistent manner like the first method. Thirdly, monthly $ET_p$ ratios can be computed from the monthly percentages of the total annual evaporation actually measured at Lana'i City.

Of the three methods considered, the third approach of estimating monthly $ET_p$ percent ages of total annual evaporation was considered the best method. Although a good rough esti mate for $ET_p$, the windward/leeward percentage of oceanic rate was not chosen because oceani rates around Lana'i have not been measured nor is this approach discretized enough both spatiall and temporally. Because $ET_p$ is a function of aerodynamic and energy processes, not rainfall, th method of $ET_p/RF$ is not a valid ratio estimation. Instead, the annual total pan evaporation can b broken down into its monthly values to incorporate the monthly variations of $ET_p$, which can the be used with other monthly estimated parameter values with equation eq.(4), pg. 18. Althoug the period of data is limited, the monthly pan data provides the most direct estimate of monthl $ET_p$. This approach is summarized in Table 8.

**Table 8. Estimate of Monthly $ET_p / ET_{annual}$ Ratios based on Pan Data**

*(Source: kem, 1964.)*

| Month[1] | $ET_p$ Average Evaporation[a] (in.) | $ET_p$ / $ET_{annual}$ Ratio[b] |
|---|---|---|
| January | 1.73 | 0.07 |
| February | 2.35 | 0.09 |
| March | 2.45 | 0.10 |
| April | 2.58 | 0.10 |
| May | 2.18 | 0.09 |
| June | 2.07 | 0.08 |
| July | 2.64 | 0.10 |
| August | 2.35 | 0.09 |
| September | 2.11 | 0.08 |
| October | 2.67 | 0.10 |
| November | 1.00 | 0.04 |
| December | 1.50 | 0.06 |
| $ET_{annual}$[c] | 25.63 | 1.00 |

a. unadjusted monthly data from Station No. 687.00, Ekem, (& others,1985), (1/57 to 12/57 period)

b. $ET_p/ET_{annual}$ = Potential evapotranspiration to total annual evapotranspiration ratio.

c. @ = for areas >2000 ft. elevation based on unadjusted data from Class A pan

To compensate for obvious areal differences, estimating monthly $ET_p$ for Lana'i was done by dividing the island into two (2) major geographical areas. In the area above the 2000-ft. elevation, $ET_{annual}$ = 25.63 inches/year, as shown in Table 2. In the area below the 2000 ft. elevation, the $ET_{annual}$ value was estimated by multiplying the mean (average) of the annual average oceanic rate of 80 inches/year by 1.2. This is based Ekern's (& others, 1985) conclusion that in dry leeward areas evaporation is up to 40% more than the oceanic rate. With a 0% difference at the shoreline and 40% increases up to the 2000 ft. elevation inland, the mean (average) increase between these elevations is assumed to be 20% greater than the oceanic rate. This corresponds to approximately 95 inches/year. Therefore, it is assumed that $ET_{annual}$ = 95 inches/year for areas below the 2000 ft. elevation contour. Now, although the calculated monthly $ET_p/ET_{annual}$ ratios in Table 2 are based in the Lanai City area which approximates the 2000-ft. elevation area, it was assumed that these ratios were consistent island-wide. Therefore, $ET_p/ET_{annual}$ ratios below the 2000-ft. elevation are the same below the 2000-ft. elevation as above. From this analysis, the resulting $ET_p$ values for areas below to 2000-ft. elevation is shown in Table 9 as follows:

**Table 9. Estimate of Monthly $ET_p/ET_{annual}$ Ratios for Areas <2000-ft. Elevation**

| Month[1] | $ET_p$ / $ET_{annual}$ Ratio | $ET_p$ Average Evaporation (in.) |
|---|---|---|
| January | 0.07 | 6.65 |
| February | 0.09 | 8.55 |
| March | 0.10 | 9.50 |
| April | 0.10 | 9.50 |
| May | 0.09 | 8.55 |
| June | 0.08 | 7.60 |
| July | 0.10 | 9.50 |
| August | 0.09 | 8.55 |
| September | 0.08 | 7.60 |
| October | 0.10 | 9.50 |
| November | 0.04 | 3.80 |
| December | 0.06 | 5.70 |
| $ET_{annual}$ | 1.00 | 95.00 |

With monthly $ET_p$ estimated for the two major areas on Lana'i, $ET_a$ can now be calculated using equations eq.(5) or eq.(8). These equations require information regarding changes in soil-moisture storage which was described in the previous section. Since $ET_a$ is the last parameter in equation eq.(4), pg. 18 we can now assess recharge.

## Recharge (*R*)

Ultimately, recharge, ***R***, is the water which makes its way to the saturated ground-wat zone and provides the foundation upon which the ground-water flow model's effective aquif parameters can be estimated. It is important to remember that ***R*** is different than infiltration, due to soil-moisture storage considerations (refer to Figure 14, pg. 35). Individual well/aquif pump test information (see Table 13, pg. 50) provides localized pockets of aquifer informatio that is not necessarily indicative of regional aquifer characteristics for many reasons describ later. However, the parameters from the water-budget calculation, in equations eq.(4) to eq.(1( are more visible, accessible, and contain a wealth of hydrologic and time series information wh compared to geologic considerations. Therefore, ***R*** is derived on a more regional and long-te basis for Lana'i than existing pump test information and provides the model with a starting flux water which provides firmer confidence in estimating the effective hydraulic parameters duri the calibration process.

Using equations eq.(4) to eq.(10), the GIS, and the previous individual parameter discu sions, a reasonable long-term value for ***R*** on Lana'i can be estimated. As defined by equatio eq.(4) to eq.(10), long-term ***R*** is the annual average recharge based on monthly variatio amongst all contributing parameters. All available data are considered and factored into the es mate of ***R***. The GIS water-budget model was initialized by starting with the average month value for $\Delta SMS_m$ after one year of simulated recharge computations.

Obviously, a longer period of record will provide a better estimate of the long-term av age for any parameter under scrutiny. Rainfall, ***RF***, has the longest period of record followed fog-drip, ***FD***, and pan or potential evapotranspiration, $ET_p$. All other water-budget paramet did not have direct data records or, in the case of irrigation return, ***IR***, were ignored. Direct ru off, ***DRO***, and changes in soil-moisture, $\Delta SMS$, and actual evapotranspiration, $ET_a$, were es mated using the long-term ***RF*** record and soil information to create ratios as discussed earlier. *F* estimation was also enhanced using a ratio to ***RF*** approach. These considerations resulted in estimated average daily island-wide ***R*** for the island of Lana'i of approximately 62 mgd which approximately 38% of total precipitation available (***RF*** + ***FD***). The ***FD*** area of the island contri uted 13.5 mgd of the 62 mgd for island-wide ***R***. Results of the GIS calculation for individ monthly parameters in equation eq.(4), pg. 18, are found in Appendix B.

It is difficult to make comparisons of this result with previous studies without recognizi comparable recharge areas or familiar units. Table 10 summarizes and compares previous lo term recharge analyses with this study's analysis in units of inches per year which is similar previous studies and familiar to local residents on Lana'i. Table 11 is the conversion of Table units to consistent units of million gallons per day (mgd) to facilitate the comparison betw studies. This study's recharge spatial distribution pattern is also shown graphically in Figure pg. 45. However, aside from the areal differences, the major difference between recharge res for this study and earlier analyses is that the nature of recharge in general is followed more clos by the GIS analysis. Recharge occurs in spurts or pulses from major rainfall events, as clea shown Figure 14, pg. 35, thus the greater discretization of time will accommodate more spurts pulses. Theis (1994) compared recharge and discharge to and from ground-water tables call them "episodic" and "more or less constant", respectively, which supports this recharge conce

## Table 10. Lana'i Annual Recharge Estimates (inches/yr)

| Author | Area (mi²) | (inches/yr) | | | | Recharge *R* (mgd) |
|---|---|---|---|---|---|---|
| | | *RF* | *FD* | *DRO* | [a]*ET*a | |
| STEARNS (1940)<br>high-level<br>remainder of island<br>Island Total | <br>15.5<br>126.8<br>142.3 | <br>35<br>19.5<br>[b]21.2 | <br>[c]NE | | <br>[d]26<br>[e]17<br>[b]17.9 | <br>6.46<br>14.80<br>21.26 |
| ANDERSON (1961) | 11.3 | 48.5 | NE | | | 4.1 to 5.5 |
| ADAMS & HUBER (1973) | 142.3 | [f]21.2 | NE | NE | [f]19.7 | [g]1.7 to 9.8 |
| BOWLES (1974) | 15.5 | [h] | [h] | | [h] | [i]6.5 |
| ANDERSON (1983) | | | NE | | | |
| MINK (1983)<br>Primary<br>Secondary<br>Total | <br>4.5<br>9.5<br>14.0 | <br>38<br>32<br>[b]33.9 | <br>22.8<br>9.6<br>[b]13.8 | <br>5.7<br>3.2<br>[b]4.0 | <br>[j]20<br>33<br>[b]28.8 | <br>7.5<br>2.4<br>[j]9.9 |
| ANDERSON (1984) | NE | [k]28.2 | [l] | NE | NE | NE |
| ANDERSON (1989)<br>Primary<br>Secondary<br>Total | <br>14<br>10<br>24 | <br><br><br>NE | <br><br><br>NE | <br><br><br>NE | <br><br><br>NE | <br>6.89<br>2.00<br>[m]8.9 |
| [n]CWRM (1990) | 14 | 28 to 35 | 13.8 | <4.0 | 26 to 28.8 | 9 |
| CWRM/USGS/LCo. GIS (1995)<br>>2000 ft. elevation<br>remainder of island<br>Island Total | <br>8.36<br>132.47<br>140.83 | <br>29.84<br>23.76<br>[b]24.12 | <br>22.28<br>0<br>[b]1.32 | <br>3.29<br>2.11<br>[b]2.18 | <br>14.92<br>13.50<br>[b]13.58 | <br>13.50<br>48.10<br>61.60 |

a. Actual evapotranspiration (& annual change in storage = 0)

b. Area weighted average estimate.

c. Not estimated

d. Steams estimated 25% of rainfall in the high-level recharge area ultimately goes to recharge. This means that Steams estimated *DRO* and *ET* to be about 75% of rainfall in the high-level recharge area, or approximately 26 inches.

e. Steams estimated 10% to 15% in the non-high-level area ultimately goes to recharge. This means that Steams estimated *DRO* and *ET* to be about 85% to 90% of rainfall in the non-high-level recharge area, or approximately 17 inches.

f. From Adams (1973) Table 3 based on Caskey (1968) methods for Waikapu, Maui recharge.

g. Range of actual pumping to estimated recharge.

h. Agrees with Steams. (High-level rainfall = 26 mgd & recharge is 25% of rainfall)

i. Also stated that ***R*** varies year to year with a range between 2 to 10 mgd.

j. Based on Mink's original descriptive calculations where ET was 20 inches/year. In his algebraic calculations, primary ***ET*** was (inadvertently or conservatively) increased to 22 inches/year resulting in his original 9.3 mgd estimation of total recharge.

k. "Effective Precipitation" defining "near-normal" (average) rainfall empirically derived as follows; 1978 rainfall data used as "near-normal" rainfall year, neglects rainfall < 0.02" or >2.50", 0.02"< 100% value of data <1.00", 1.00"< 50% value of data< 2.50.

l. Disputes Mink's fog-drip estimates of 60% and 30% of rainfall in two areas. However, offers no estimate except acknowledges that fog-drip "unquestionably contributes to recharge".

m. Based on Anderson's total of primary (0.492 mgd/sq. mi.)and secondary (0.20 mgd/sq. mi.) recharge areas. Breakdown of individual parameters not given. Based on new information from Wells 6 & 7 and Ekern's (1964) fog-drip study.

n. Synopsis of reasonable range of values from previous studies. Area is recharge area

**ADDITIONAL NOTES**: all footnotes also apply to Table 11

## Table 11. Lana'i Annual Recharge Estimates (mgd)

| Author | Area (mi²) | (mgd) | | | | |
|---|---|---|---|---|---|---|
| | | *RF* | *FD* | *DRO* | *$ET_a$* | *R* |
| STEARNS (1940) | | | | | | |
| high-level | 15.5 | 25.8 | [c]NE | | [d]19.3 | 6.46 |
| remainder of island | 126.8 | 117.7 | | | [a]102.9 | 14.80 |
| Island Total | 142.3 | [b]143.5 | | | [b]122.2 | 21.26 |
| ANDERSON (1961) | 11.3 | 26.1 | NE | | | 4.1 to 5.5 |
| ADAMS & HUBER (1973) | 142.3 | [f]143.5 | NE | NE | [f]133.8 | [g]1.7 to 9.8 |
| BOWLES (1974) | 15.5 | [h] | [h] | | [h] | [i]6.5 |
| ANDERSON (1983) | | | NE | | | |
| MINK (1983) | | | | | | |
| Primary | 4.5 | 8.1 | 4.9 | 1.2 | [j]4.3 | 7.5 |
| Secondary | 9.5 | 14.5 | 4.3 | 1.4 | 15.0 | 2.4 |
| Total | 14.0 | [b]22.6 | [b]9.2 | [b]2.6 | [b]19.3 | [j]9.9 |
| ANDERSON (1984) | NE | [k]28.2 | [l] | NE | NE | NE |
| ANDERSON (1989) | | | | | | |
| Primary | 14 | | | | | 6.89 |
| Secondary | 10 | | | | | 2.00 |
| Total | 24 | NE | NE | NE | NE | [m]8.9 |
| CWRM ^(1990) | 14 | 18.7 to 23.3 | 9.2 | <2.7 | 17.3 to 19.2 | 9 |
| CWRM/USGS/LCo. GIS (1995) | | | | | | |
| >2000 ft. elevation | 8.36 | 11.88 | 8.87 | 1.31 | 5.94 | 13.50 |
| remainder of island | 132.47 | 140.28 | 0 | 12.44 | 79.74 | 48.10 |
| Island Total | 140.83 | [b]152.16 | [b]8.87 | [b]13.75 | [b]85.68 | 61.60 |

<u>NOTES</u>: (see Table 10 footnotes) rounding occurs in figures to be consistent.

TO BE UPDATED

Figure 15. Lana'i Ground-Water Recharge Isograms

There are several points to make concerning Table 10, Table 11, and the comparison wi previous overall island-wide recharge results. Stearns (1940) and Adams (& others, 1973) a previous studies which specifically addressed the island-wide recharge. Mink (1983), discount Adam's estimate stating that he "*employed an unrealistic evapotranspiration rate for the hi region of the island*". Adam's approach is suspect since it is not complete and uses ***ET*** estim tions derived for the Waikapu area on the island of Maui. Also, Adams's primary objective was locate well sites on the windward side of the island for reforestation purposes and not to estima sustainable yield for Lana'i. Therefore, Adam's small estimate for recharge is not considered ri orous enough to be valid nor comparable to other studies. Considering Stearns analysis, volume rically, there is at least a 6% increase in the estimated average annual rainfall rate, ***RF***, from t GIS analysis. Due to the longer record of rainfall data available for this study such an increase not unreasonable and is, in fact, considered a better estimate with greater foundation. Ev Stearns noted that the available rainfall data during his survey was limited by stating: "*The rai fall records are too short to determine reliable averages*". Fog-drip, ***FD***, was not considered l Stearns and cannot be compared directly. Since direct runoff, ***DRO***, and actual evapotranspir tion, $ET_a$, were combined in Stearns's analysis it is hard to make a direct comparison betwe these hydrologic parameters. Volumetrically, there is approximately a 30% decrease in the es mated average annual $ET_a$ from Stearns to the GIS estimate. Since ***DRO*** appears to constitu only a small portion of the water-budget and all other factors except the length of time-series da is common, this decrease can be firmly attributed to the monthly basis of ***R*** calculation combin with the changes in soil-moisture storage, $\Delta SMS$, considerations. These two considerations, discussed earlier, should result in a lower estimate of actual evapotranspiration, $ET_a$ than by usi annual averages based on yearly totals. Other parameters were not comparable at this island-wi scale since they were not directly addressed. Therefore, it can be concluded that the two maj differences between the island-wide GIS analysis and previous studies has been the reduction $ET_a$ and the addition of ***FD***. The GIS island-wide ***R*** estimate is almost three times the islan wide recharge amount estimated by Stearns and is attributable, at least in part, to these two maj differences.

Several points can be made concerning Table 10, Table 11, and the comparison with pre ous ***R*** results in the ***FD*** area. Mink (1983), Anderson (1984 & 1989) and the CWRM (1990) a previous studies which specifically addressed the impact of ***FD*** on Lanai's ground-wa recharge. Stearns and Bowles (1974) also concentrated on comparable ***FD*** areas but did r quantify ***FD***. There are only approximate areal comparisons of ***FD*** influenced areas ranging fr a low of 8.36 to a high of 15.5 square miles. The GIS analysis has the lowest area influenced ***FD***; 8.36 square miles. Volumetrically, the estimated annual average ***RF*** in the ***FD*** area is lov from the GIS approach than previous studies by a maximum of 47%, corresponding to Mi This is mostly attributable to the difference in area where the GIS considered 40% less area th Mink. Volumetrically, the estimated average annual ***FD*** is about 4% less in the GIS analysis th the previous studies. However, this total amount of ***FD*** estimated by the GIS is concentrated o 40% less area. Volumetrically, the estimated average annual ***DRO*** is approximately 50% less the GIS than in the previous studies and the majority of this, too, is attributable to the difference the ***FD*** area. Like the island-wide scope, the $ET_a$ was lower in the GIS approach for the ***FD*** ar but by a greater percentage; 69%. However, unlike the island-wide scope, the difference in area, about 40% less, accounts for about one-half of this percentage difference between studi

The other half, approximately 30%, is due to the monthly basis of ***R*** calculation combined with $\Delta SMS$ considerations as evidenced by Table 10, pg. 43, which shows the resulting inches/yr rate for $ET_a$ significantly less in the smaller GIS ***FD*** area. One would think that in the ***FD*** area the more concentrated presence of ***FD*** would provide more water in soil-moisture storage available for potential evapotranspiration, thus $ET_p$ can be more readily achieved. It follows that in areas lacking ***FD*** there are definitely more times when there isn't much soil-moisture storage available for $ET_p$ to be achieved. Hence, one would expect that there should be *less* of a difference in the ***FD*** area's estimated $ET_a$ between earlier studies and the GIS than the ***non-FD*** areas estimated $ET_a$ since there is more opportunity for $ET_p$ to be achieved and earlier studies assumed that annual pan evaporation rates were met. However, this is an additional example of the impact that the monthly basis of calculating and $\Delta SMS$ considerations have on estimating annual averages. Figure 16 plots the monthly variation of the water-budget parameters. As can be seen in Figure 16, summer months do not have as much water to meet the $\Delta SMS$ requirements as do winter months. For example and from Appendix B, in the month of June there is an average infiltration of only 1.30 inches while the $ET_p$ is 2.64 inches (see Table 2, pg. 28), of which only an average of 1.17 inches is calculated to actually evaporate. Therefore, $ET_p$ is not achieved for this month even in the ***FD*** area. Thus, despite the area differences which affect the volumetric averages it can be concluded that the two major differences between the GIS ***FD*** area and previous studies is the concentration of ***FD*** over a smaller area and the reduction of $ET_a$. The GIS ***FD*** area ***R*** estimate is approximately double Stearns and Bowles estimate and about 50% more than Mink, Anderson, and the CWRM estimates and is attributable, at least in part, to these two major differences.

**TO BE UPDATED**

Figure 16. GIS Monthly Variation of Individual Recharge Parameters in ***FD*** Area

Overall, it can be said that the major differences in the results between the GIS methodc ogy and previous studies is due to the lower estimate of $ET_a$ and the concentration of ***FD*** over smaller area. Despite the higher level of precision in the GIS method, all previously investigat parameters, with the exception of island-wide $ET_a$, did not differ greatly when areal differenc are considered. There may be a cumulative effect of these smaller differences but the results inc cate that these differences offset rather than amplify one another. For example, in the ***FD*** are though the GIS estimates less ***DRO*** than Mink's there is also less ***RF*** and ***FD*** due to the differi areal domain. Also, it is interesting to note that $ET_a$ due strictly to the month-to-month basis calculation and $\Delta SMS$ considerations are at about the same rate for ***FD*** and ***non-FD*** areas; abo 30% of ***RF***.

A recharge scenario devoid of ***FD*** was investigated due to the concern over the health the fog forest on Lana'i and the corresponding potential impacts on Lanai's ground-wat resources. If the forest leaf area is significantly lowered than ***FD*** may be affected similarly. T conservative approach was taken where all ***FD*** was removed although its total absence is unlike The results of this analysis are summarized in Table 12 below.

**Table 12. *FD* vs. No *FD* Recharge Estimates**

| FD Status | Author | Area (mi²) | (mgd) RF | FD | DRO | $ET_a$ | R |
|---|---|---|---|---|---|---|---|
| FD | CWRM/USGS GIS (1994) | | | | | | |
| | >2000 ft. elevation | 8.36 | 11.88 | 8.87 | 1.31 | 5.94 | 13.5 |
| | remainder of island | 132.47 | 140.28 | 0 | 12.44 | 79.74 | 48. |
| | Island Total | 140.83 | 152.16 | 8.87 | 13.75 | 85.68 | 61. |
| No FD | CWRM/USGS GIS (1994) | | | | | | |
| | >2000 ft. elevation | 8.36 | 11.88 | 0 | 1.31 | 5.49 | 5. |
| | remainder of island | 132.47 | 140.28 | 0 | 12.44 | 79.74 | 48. |
| | Island Total | 140.83 | 152.16 | 0 | 13.75 | 85.23 | 53. |

As can be seen from Table 12, the effect of ignoring ***FD*** is an 8.87 mgd loss to ***R*** in t areas above the 2000 ft. elevation resulting in a decreased estimate of ***R*** for the ***FD*** area fr 13.50 to 5.08 mgd. The reduction to island-wide ***R*** is small, 14%, compared to the reduction to in the ***FD*** influenced area; 62%. This clearly indicates that ***FD*** constitutes a major portion of ***R*** the ***FD*** area.

Finally, ***DRO*** that is captured in the Palawai basin topographical depression and has a f ther chance of infiltration was investigated. It was found that about an additional 1 mgd could added to ***R*** for this consideration. Given that this constitutes less than 2% of the island-wide with ***FD*** and without ***FD*** it was assumed that this ignorance of captured ***DRO*** is not a signific error on the regional scale.

## Existing Wells, Historical Pumpage, and Water Levels

There are twenty-four (24) wells with information helpful to the modeling effort. A new well, Well 14 is currently under construction. The location of these wells are shown Figure 1, pg. 2. These wells and their information relevant to producing a flow-model are listed in Table 13, pg. 50, and Figures 17 through 30. Individual chloride information has been omitted to emphasize the flow-type nature of the model. Both water levels and pumpage from these wells vary temporally according to seasonal and operational changes and are shown for each well and the cumulative pumpage in Figures 17 through 30. Magnified views of monthly water level responses for each well can be found in Appendix H.

On an island-wide basis, Lana'i has a long record of both pumpage and water level data. The historical record of pumpage and water level data spans from 1926 to the present. Records from 1926 to 1939 and 1942 to 1985 were found on file at the USGS and records from 1988 to the present are found in CWRM files. Records for 1986 through 1987 were provided by LCo.

Aquifer hydraulic parameters are also listed in Table 13. The three (3) hydraulic parameters listed are hydraulic conductivity, ***K***, transmissivity, ***T***, and the storage coefficient, ***S***. These parameters, their significance, and how they are obtained were discussed earlier and in more detail. It is important to note that there are nine (9) estimates for ***K*** and ***T*** but only one (1) estimate for ***S***. This highlights the fact that *single-well* pumping tests were the conditions under which the majority of these parameters were obtained. Therefore, for reasons outlined earlier, these values were obtained under less than ideal situations. Thus, errors are present it should be understood that the values in Table 13, pg. 50, are not absolute nor necessarily accurate. However, they do provide a reasonable range to begin the flow model parameter estimation process. Where possible, reported values were checked using pump analysis software (Geraghty, 1989).

The average ***K*** of nine (9) high-level pump tests is 18.3 ft/day. Typical values for ***K*** in basalt can range from $10^{-7}$ to $10^{5}$ f./day (Heath, 1982). Research by Sooros (1973) estimated the range for Pearl Harbor flank flows between 7 to 8500 ft/day. For dike complexes outside of caldera regions on southeastern Oahu, Takasaki (& others, 1982) had estimated a range for ***K*** from 1 to 500 ft/day. Therefore, the average ***K*** is for Lana'i is consistent with values for dike complexes. However, several of these pump tests, specifically wells 1, 3, and 9 are known to have encountered flow boundaries. Therefore, ***K*** values are probably higher than those estimated from past pump tests. Also, ***K*** values were estimated by consultants assuming different aquifer thicknesses. Additionally, the pump test for Shaft 1 indicates a much higher ***K*** for the basal regions of Lana'i.

The average ***T*** of nine (9) high-level pump tests is 7,854 $ft^2$/day. However, ***T*** values are not accurately known because accurate high-level aquifer thicknesses, ***b***, are unknown.

Typical values for ***S*** range from 0.1 to 0.3 for unconfined aquifers. However, only one (1) estimate for ***S*** was made by Mink (1983) based on an observation well, T-2, data. ***S*** is important for transient model simulations only. As stated earlier, ***S*** could be 41 times for a lens type situation. However, since the high-level aquifer is not known to follow the Gyhben-Herzberg relationship, unknown lag-time considerations of transition zone movement, and transmissivity would have to be modified as well, it is probable that 0.1 to 0.3 is a reasonable range.

## Table 13. Existing Lana'i Wells

| Well No. | Well Name | Year Initially Drilled | Initial Water Level Elevation (ft. msl) | Initial Bottom of Well Elevation (ft. msl) | *K* (ft/day) | *T* (ft²/day) | *S* | Historical Pumpage Water Levels |
|---|---|---|---|---|---|---|---|---|
| 4454-01 | Manele | [a]na | 2.5 | na | na | na | na | na |
| 4552-01 | Well 12 | 1990 | 5 | -25 | | | na | na |
| 4553-01 | Well 13 | 1990 | 0 | -25 | | | na | na |
| 4555-01 | Well 10 | 1989 | 208 | 208 | | | na | na |
| 4852-01 | MH Tunnel | 1918 | Dry | 2,700 | na | na | na | na |
| 4852-02 | Well 5 | 1950 | 1,570 | 1174 | [bc]16.4 | [bc]6,412 | na | Figure 17 |
| 4852-03 | USGS T-2 | | | | [bc]11.2 | [bc]4,355 | [b]0.1 | na |
| 4853-01 | Gay Tunnel | 1920 | Dry | 1,920 | na | na | na | na |
| 4853-02 | Well 1 | 1945 | 818 | -3 | [de]4.8 | [de]3,740 | na | Figure 18 |
| 4854-01 | Well 9 | 1990 | [f]808 | 446 | [de]3.2 | [de]2,670 | na | Figure 19 |
| 4952-01 | Waiapaa T. | 1924 | Dry | 2,220 | na | na | na | na |
| 4952-02 | Well 4 | 1950 | 1,589 | 1,149 | [bc]6.0 | [bc]2,663 | na | Figure 20 |
| 4953-01 | Well 2 | 1946 | 1,544 | 903 | | | na | Figure 21 |
| 4953-02 | Shaft 3 | 1954 | 1,553 | [g]1,510 | | | na | Figure 22 |
| 4954-01 | Well 3 | 1950 | [h]1,124 | 651 | [bce]6.1 | [bce]2,902 | na | Figure 23 |
| 4954-02 | Well 8 | 1990 | 1,014 | 412 | [i]16.5 | [j]9,900 | na | Figure 24 |
| 5053-01 | Lower Tunnel | 1911 | 1,103 | 1,103 | na | na | na | Figure 25 |
| 5053-02 | Upper Tunnel | 1911 | 1,500 | 1,500 | na | na | na | Figure 26 |
| 5054-01 | USGS T-3 | 1950 | [k]1,064 | gmd-928.6 | na | na | na | na |
| 5054-02 | Well 6 | 1986 | 1,005 | 600 | [l]88.6 | [l]35,640 | na | Figure 27 |
| 5055-01 | Well 7 | 1987 | 650 | 450 | [l]12 | [c]2,400 | na | na |
| 5149-01 | Gay Well A | 1900 | 2 | -44 | na | na | na | na |
| 5154-01 | Shaft 2 | 1938 | 735 | 479 | na | na | na | Figure 28 |
| 5253-01 | Shaft 1 | 1936 | 2.4 | 1.4 | [m]4,500 | [m]450,000 | na | Figure 29 |
| TOTAL Data | 24 wells | na | 22 | 20 | 9 | 9 | 1 | Figure 30 |
| AVERAGE | na | na | na | na | [n]18.3 | [n]7,854 | 0.1 | Figure 30 |

a. not available
b. Mink (1983), Jacob's Method & b = initial head to bottom of well (u=0.08 @ T2).
c. based on recovery data & Theis method.
d. Nance (1993), Jacob's Method & b = initial water level above sea level.
e. Probable boundary encountered
f. Updated from K. Takasaki investigation and resurveyed ground elevation information.
g. based on Stearns (1953 & 1959) length of tunnel behind bulkhead is 745.5 ft.
h. based on Stearns (1959).
i. Pump test report M&E Pacific (1951), Modified Soroos Method.
j. b= water table to bottom of well.
k. based on Stearns (1959).
l. Soroos Method (1973) modified.
m. Based on Theis equation although Theim is more appropriate no observation. wells (Takasaki, & others, 1982); probably too high.
n. not including results from Shaft 1 since it is a basal source.

**Other Notes to Table 13**

*K* = estimated hydraulic conductivity.
*T* = estimated transmissivity.
*S* = storage coefficient.
msl = mean sea level

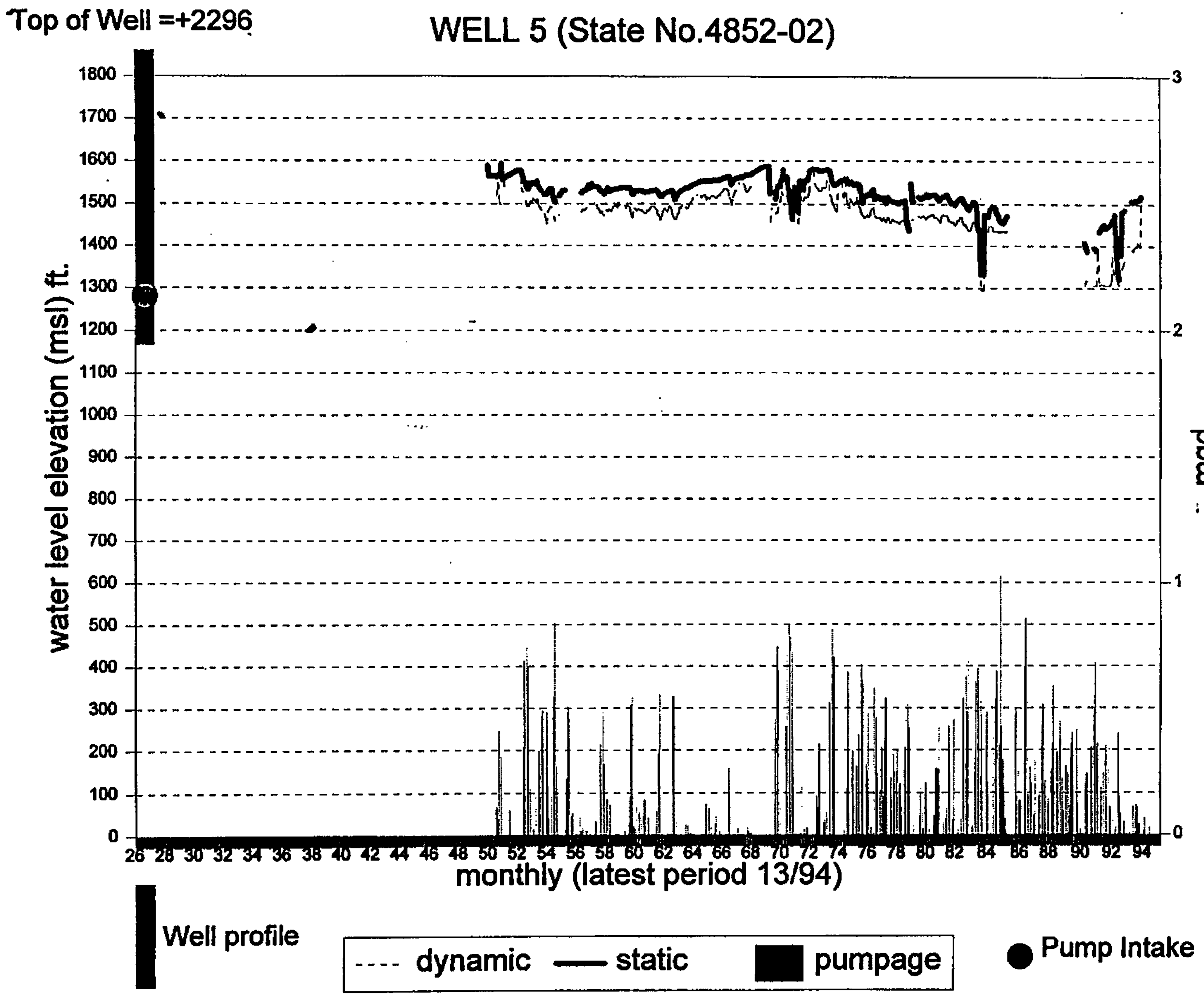
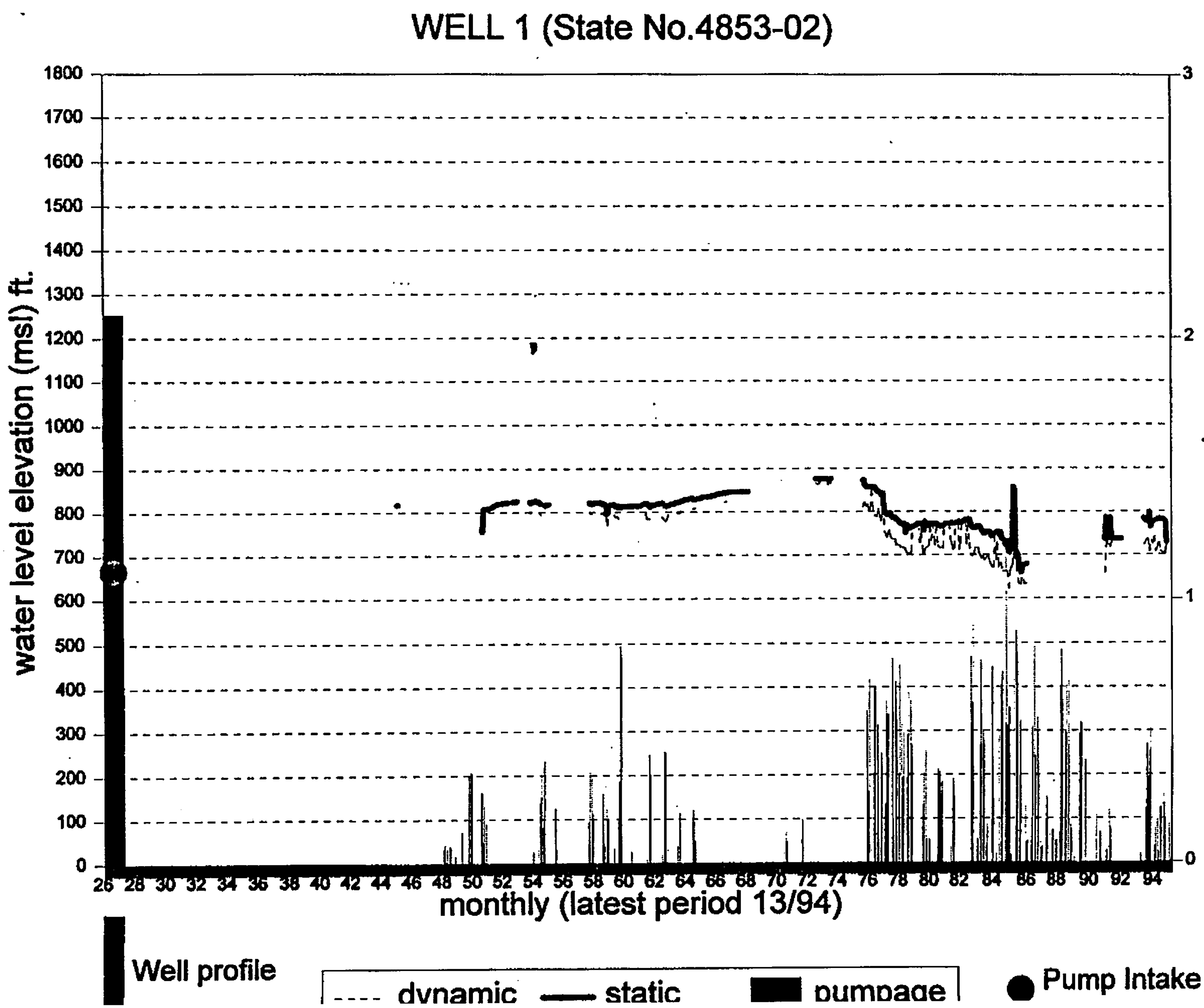



Figure 17. Well No.4852-02, Well 5 Historical Pumpage and Water Levels

September 13, 1995 PRELIMINARY DRAFT - SUBJECT TO CHANGE


WELL 1 (State No.4853-02)
water level elevation (msl) ft.
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
mgd
3
2
1
0
26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94
monthly (latest period 13/94)
Well profile
dynamic
static
pumpage
Pump Intake

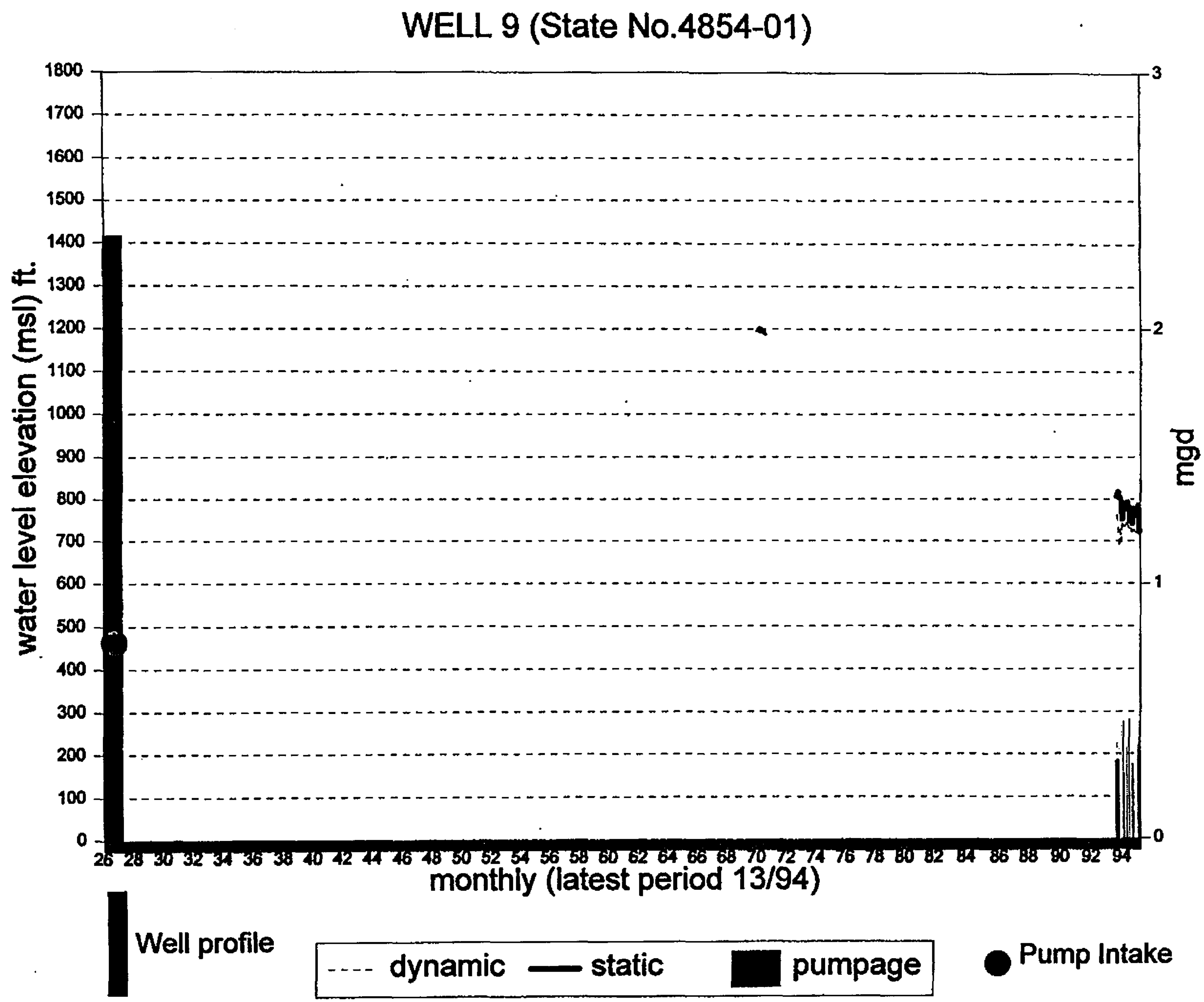



Figure 19. Well No.4854-01, Well 9 Historical Pumpage and Water Levels

September 13, 1995 PRELIMINARY DRAFT SUBJECT TO CHANGE

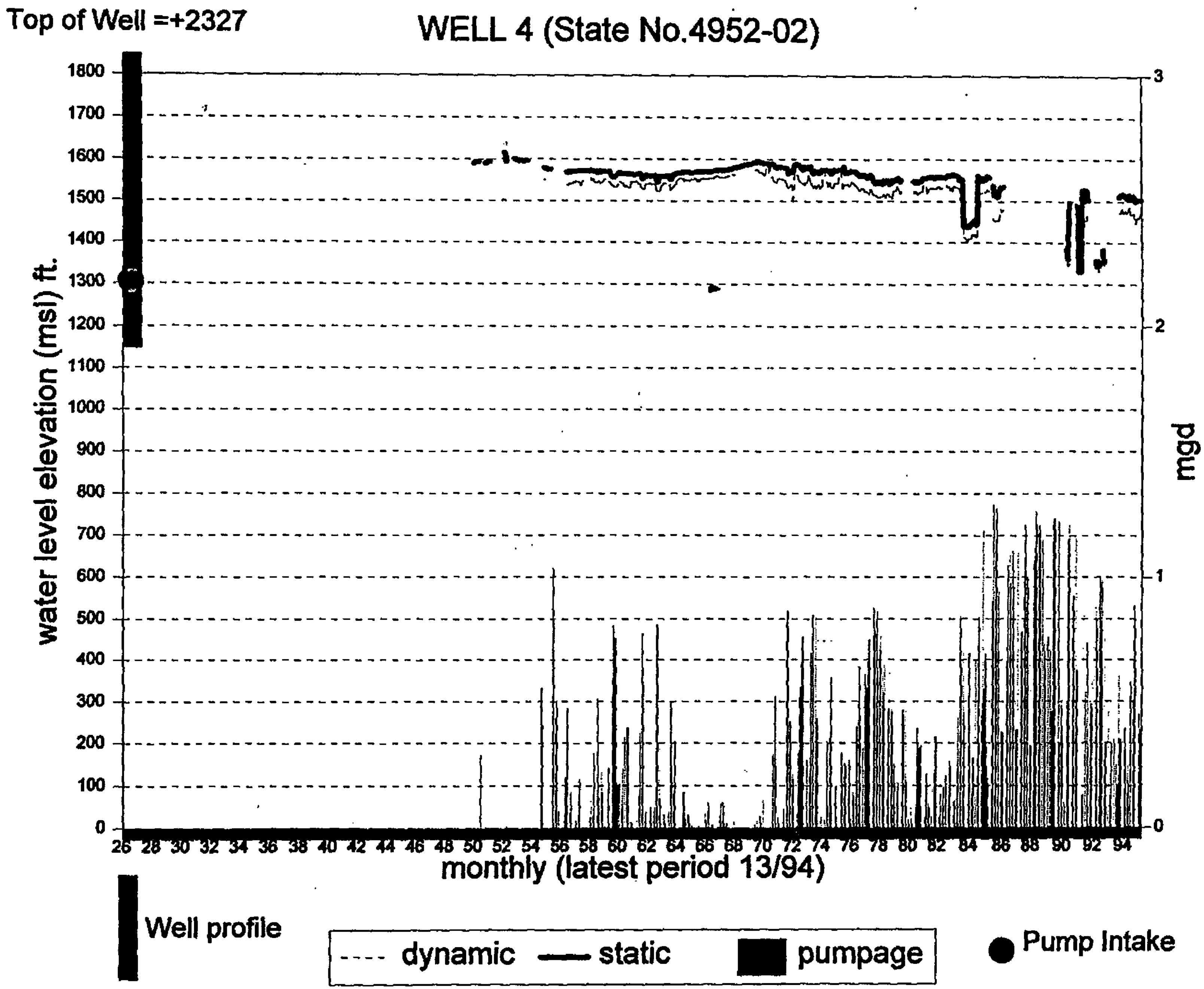



Figure 20. Well No.4952-02, Well 4 Historical Pumpage and Water Levels

September 13, 1995 PRELIMINARY DRAFT - SUBJECT TO CHANGE

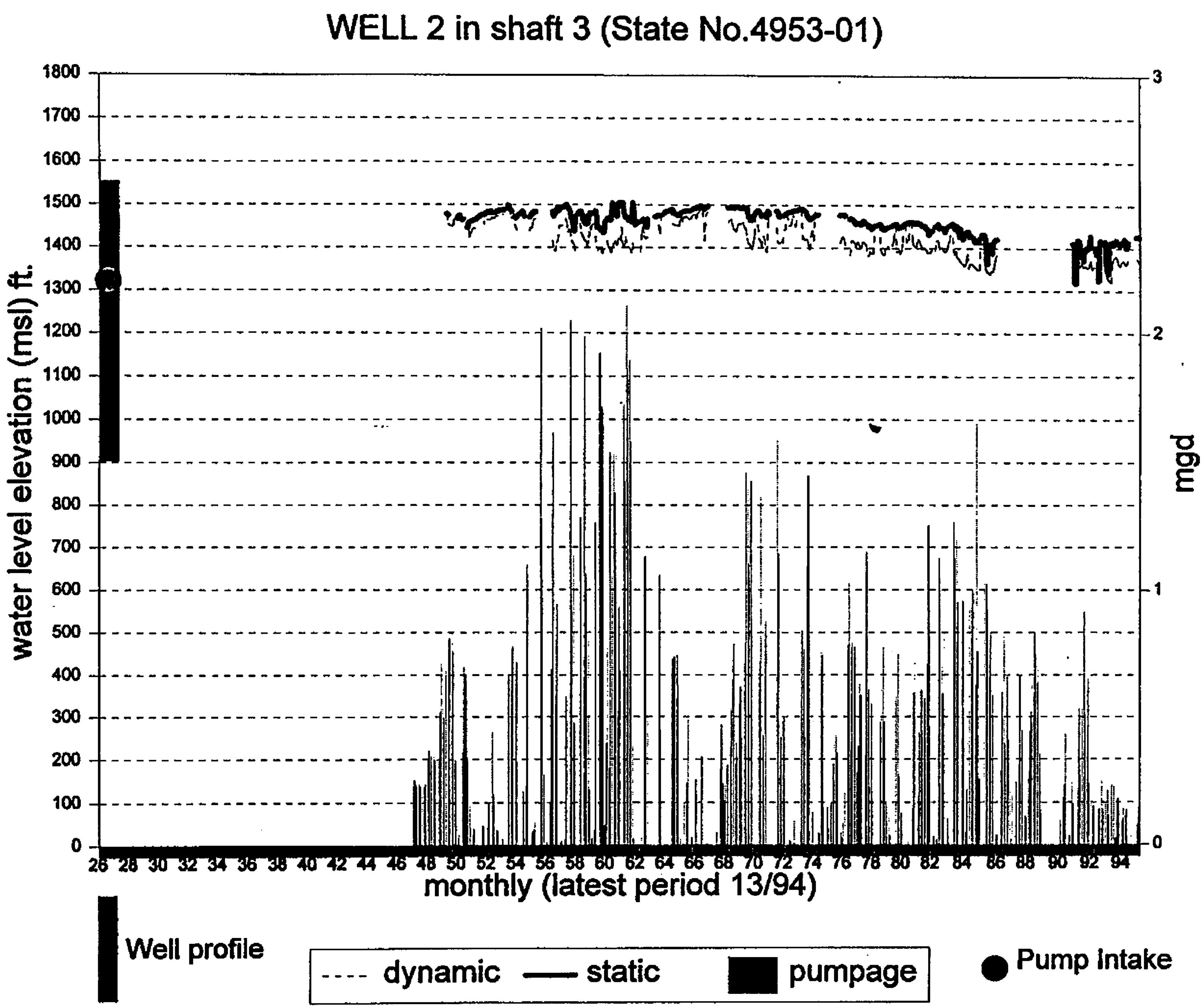
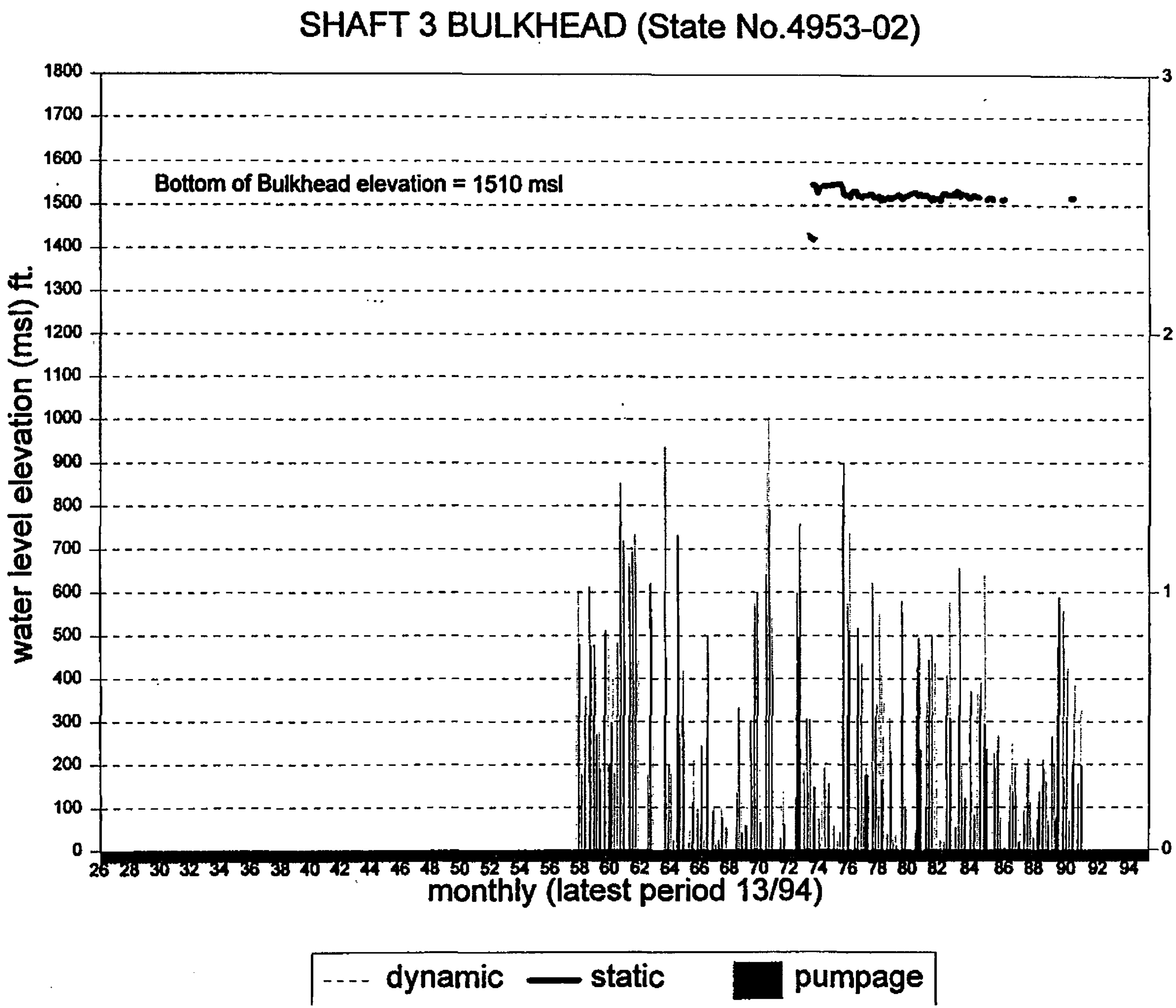



Figure 21. Well No.4953-01, Well 2 Historical Pumpage and Water Levels

September 13, 1995 PRELIMINARY DRAFT - SUBJECT TO CHANGE




September 13, 1995 PRELIMINARY DRAFT - SUBJECT TO CHANGE

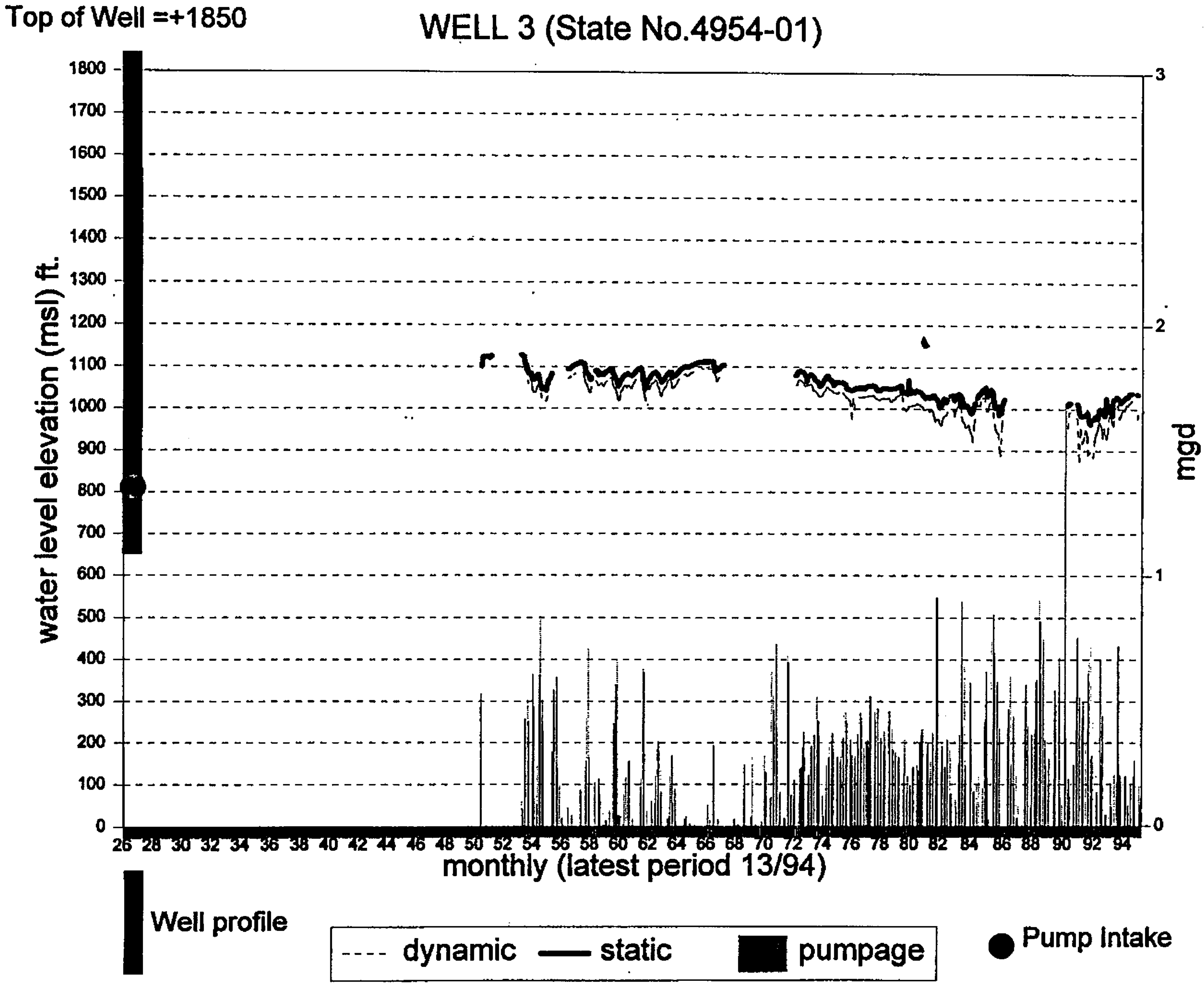
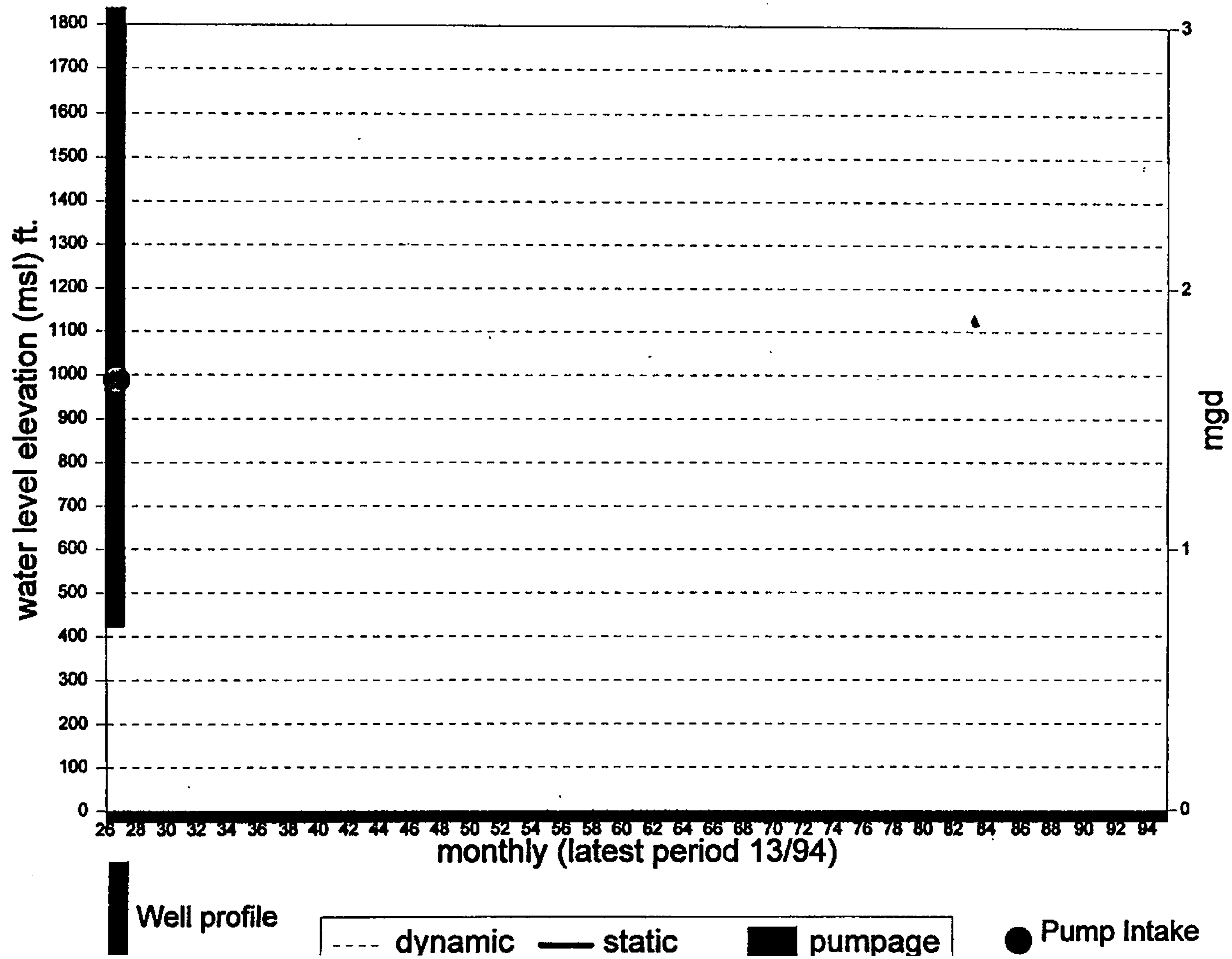



Figure 23. Well No.4954-01, Well 3 Historical Pumpage and Water Levels

September 13, 1995 PRELIMINARY D[illegible]T - SUBJECT TO CHANGE

Top of Well =+1902

WELL 8 (State No.4954-02)



LOWER MAUNALEI TUN (State No.5053-01)

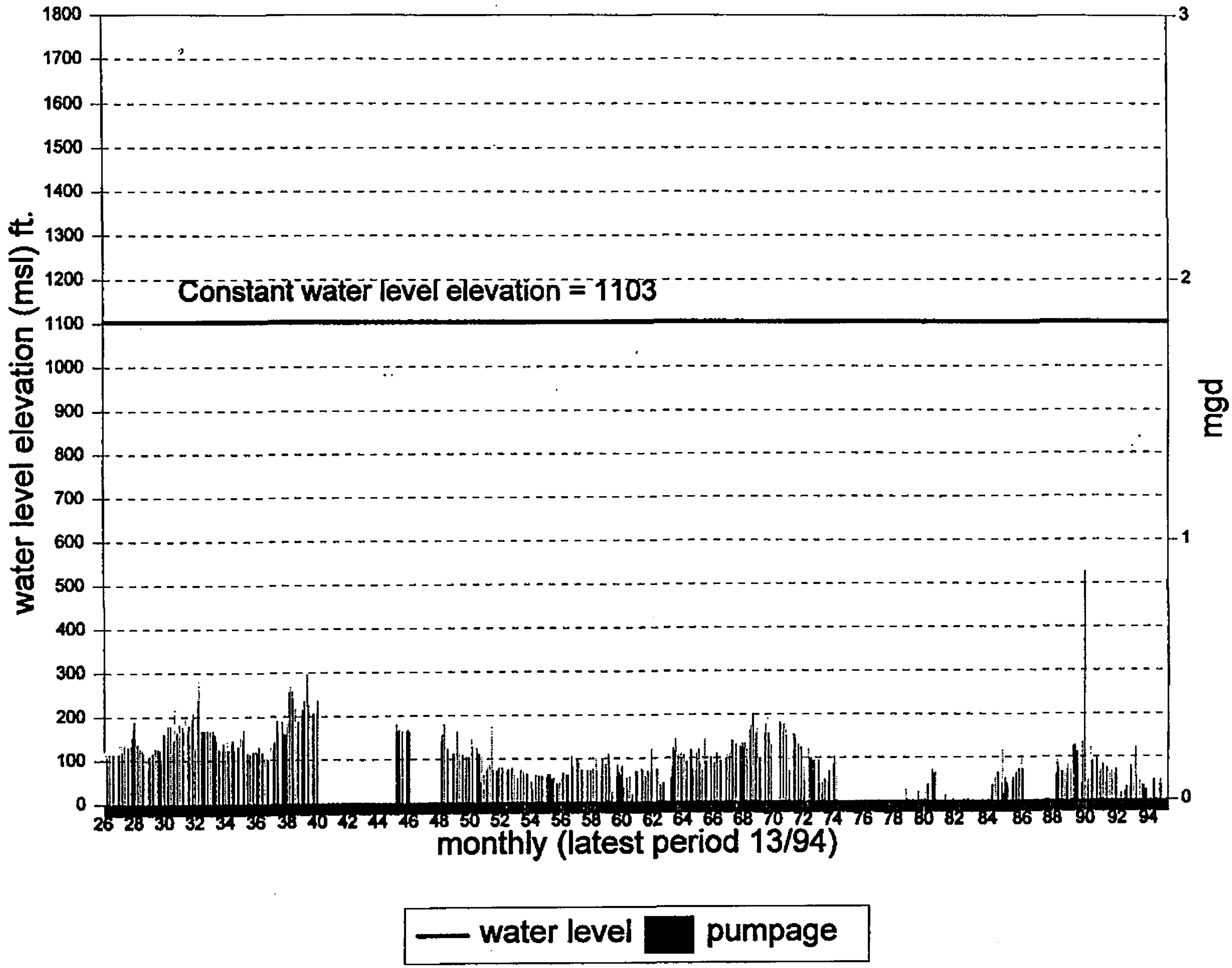
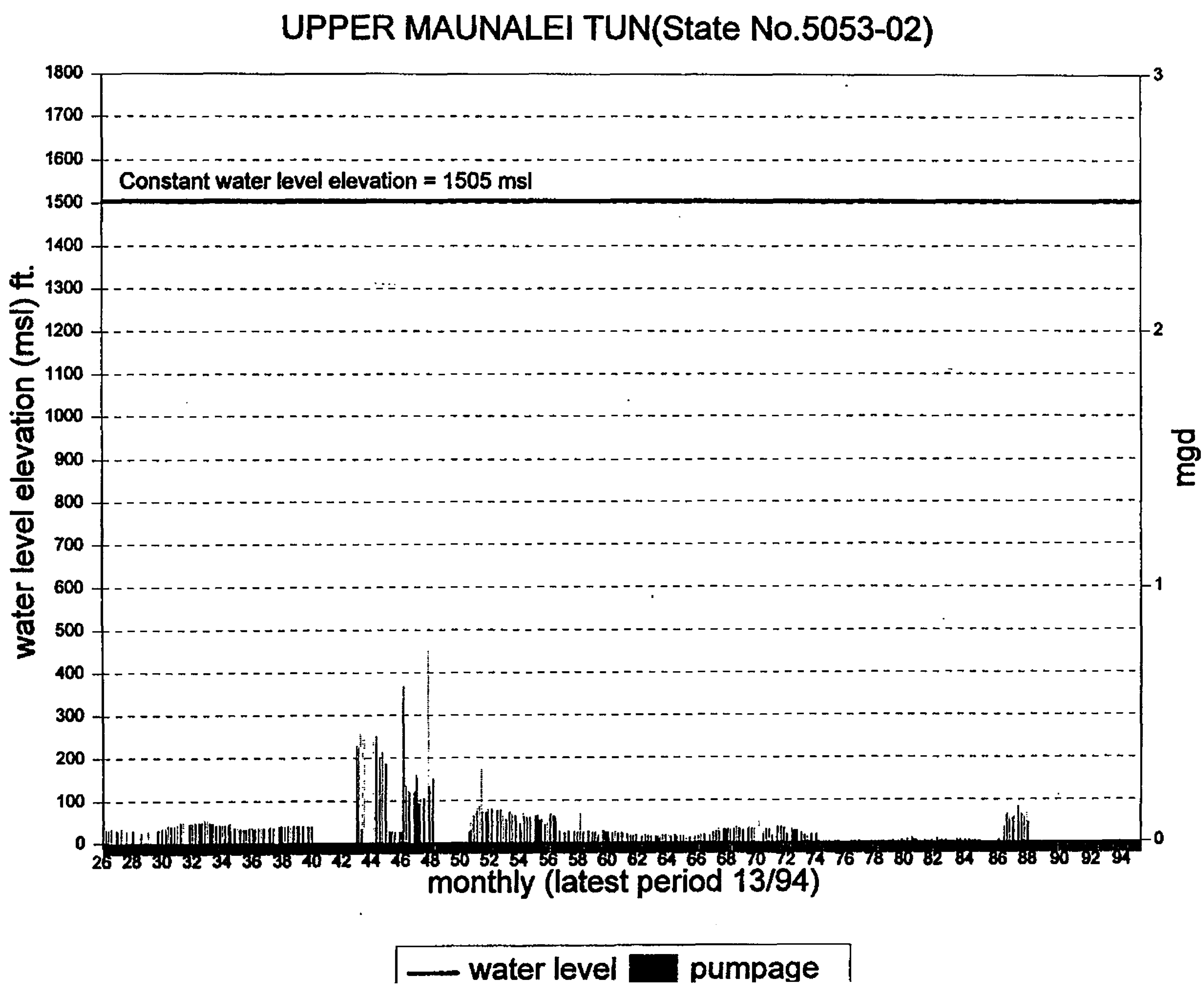



Figure 25. Well No.5053-01, Lower Tunnel Historical Pumpage and Water Levels




September 13, 1995 PRE[illegible]IINARY DRAFT - SUBJECT TO CHANG

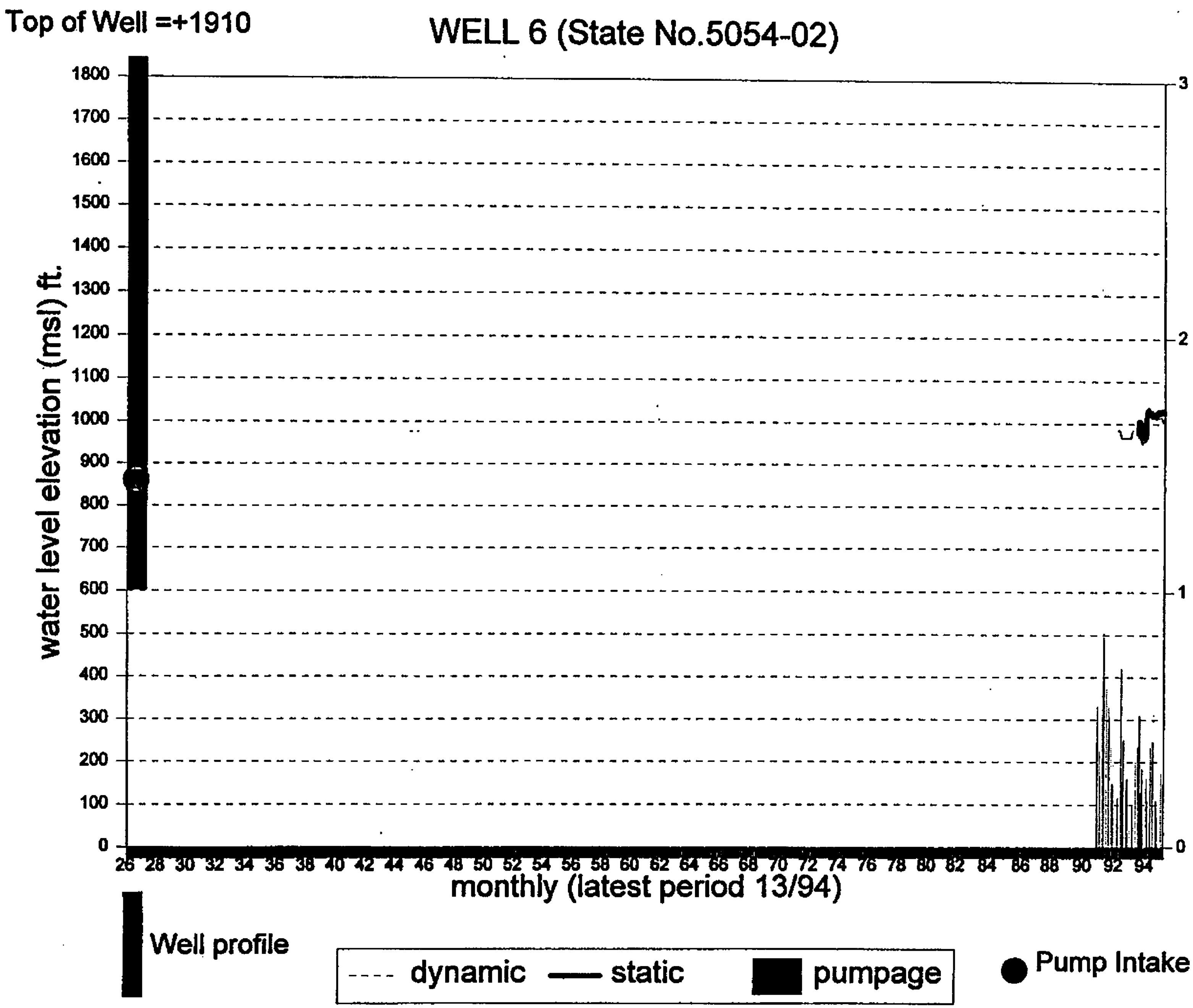
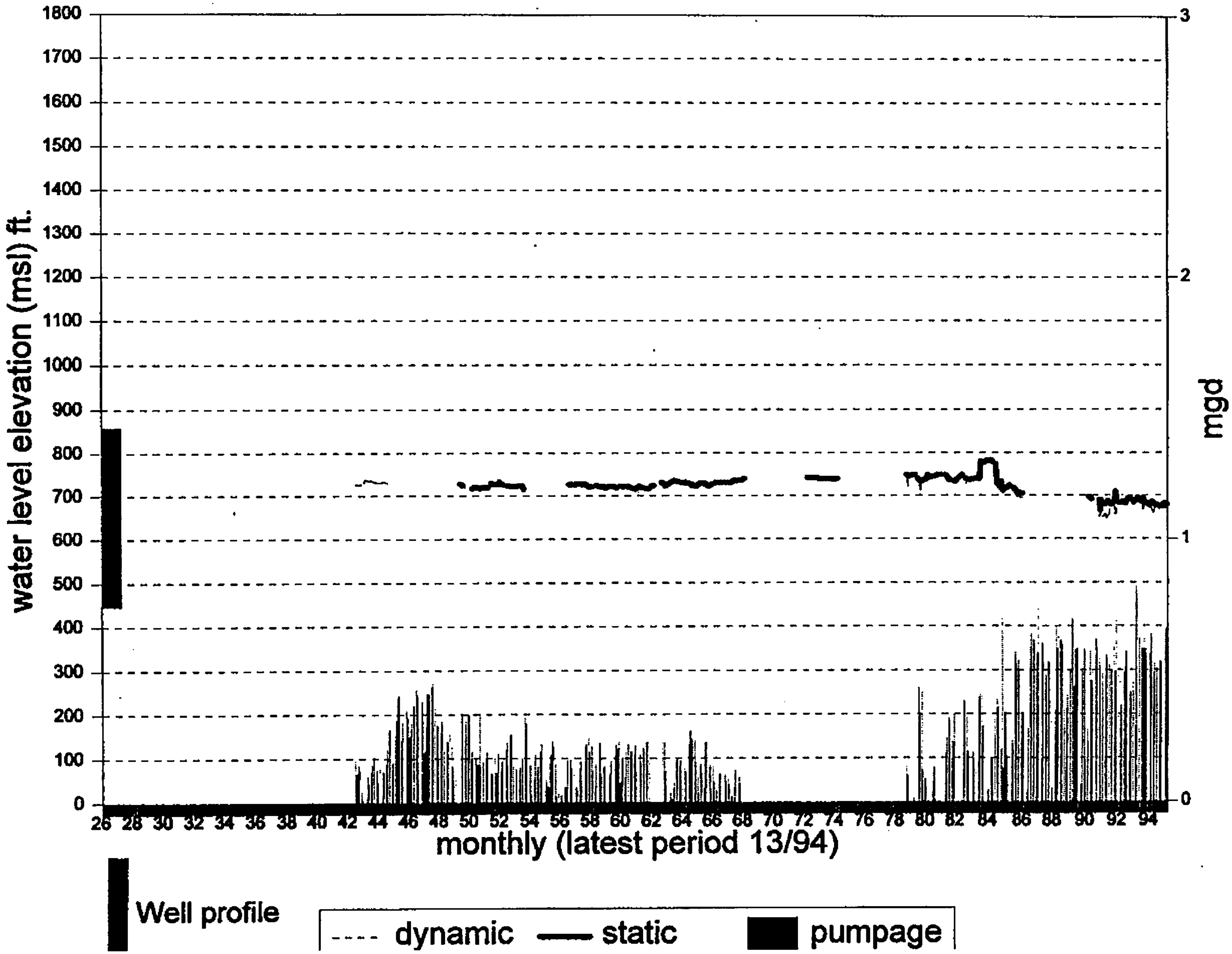



Figure 27. Well No.5054-02, Well 6 Historical Pumpage and Water Levels

# SHAFT 2 (State No.5154-01)



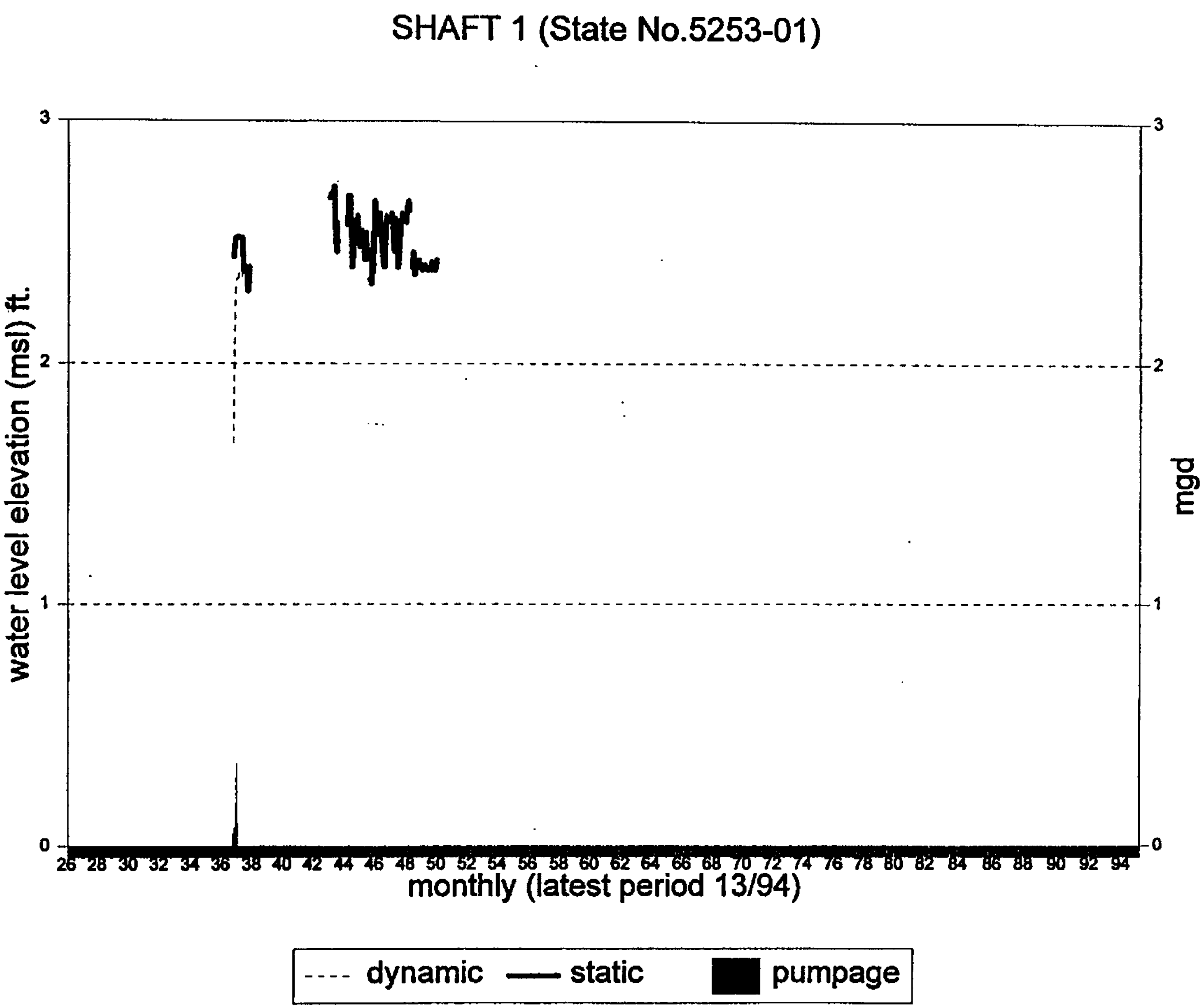
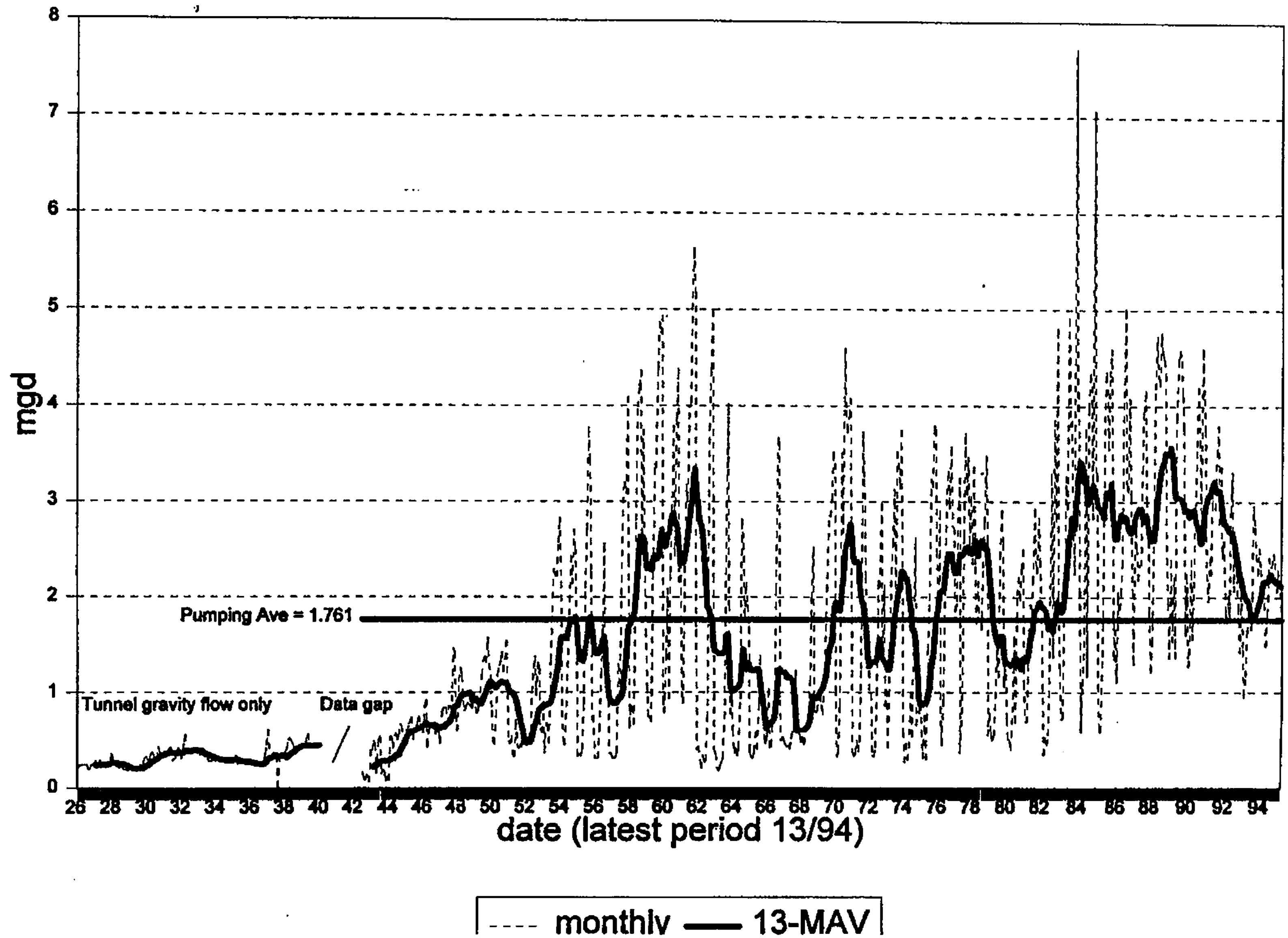


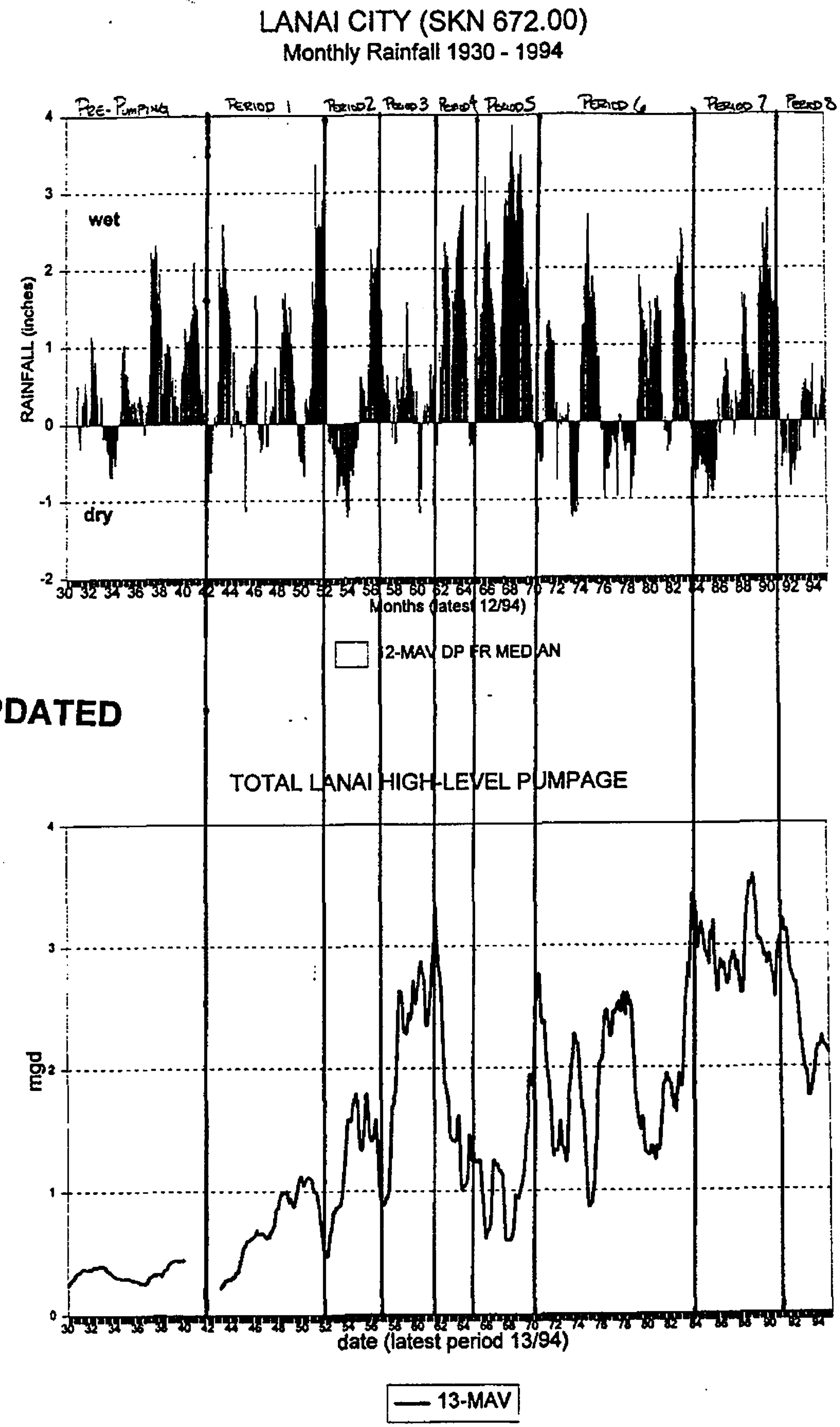

Figure 29. Well No.5253-01, Shaft 1 Historical Pumpage and Water Levels

September 13, 1995 PRELIMINARY DRAFT - SUBJECT TO CHANGE

# TOTAL LANAI HIGH-LEVEL PUMPAGE




September 13, 1995 PRE INARY DRAFT - SUBJECT TO CHANG




**TO BE UPDATED**

Figure 31. Selected Periods of Drawdown Levels on Lana'i

It is important to note that there are gaps in the data for both water levels and pumpag( Part of the reason for the Maunalei sources' data gap in the late '60s through the late 70's were combination of a flooding event in Shaft 2 and problems with the distribution system going up th pali (McCullough, personal communication, 4/22/95). Gaps in the data for other sources are sin ply indicative of the intermittent nature of pumpage and the lack of taking water levels betwee pumping and non-pumping times. There are also spikes in the data which do not seem reasor able. Upon checking original recorded data with LCo. and consultant reports (Anderson, 198: some of these spikes were corrected and such corrections are reflected in Figures 17 through 3( Other spikes could not be rectified. However, despite these problems with the water level an pumpage data the overall historical data necessary for model calibration is good.

Water level data on Lana'i were and continue to be measured via pressurized airlines fc both pumping and non-pumping conditions on continuous water level charts. Pumping water lev els are reported as the lowest water levels during a particular month. Pumping water levels, c dynamic water levels, always include some turbulent and frictional losses, which are primarily th function of well design, construction, and development and add to the theoretical drawdown in well. Non-pumping, or static, water levels are more representative of an aquifer's water leve response to stresses and are more important in the model calibration effort than pumping wate levels. This is because MODFLOW does not account for pumping well losses. Static water lev els on Lana'i were taken at least one-day after pumps were turned off although measuremen after longer periods, sometimes several months, of pump shut-off are also common. The stati water level was and continues to be reported as highest water level during a particular month.

There are definite general trends in the water level data. Specifically, the rising trends i some of the wells in the absence of any long-term changes in rainfall patterns (Figure 10, pg. 2: and corresponding fluctuations in total pumpage (Figure 30, pg. 64) during the 1960's are curiou Bowles (1974) attributed the steady rising water level trend in Shaft 2 (Figure 28, pg. 62) durin the 1960's to reforestation and drainage programs initiated in the 1920's by Dole Plantation. Th same may be said of Well 1 (Figure 18, pg. 52). From the early 70's to the late 80's a gener decline in water levels occurs between the ranges of 100 to 275 feet; a period of increasing pum age. Since the early 90's, water levels have recently been recovering due to the cessation ( pumpage for pineapple which significantly lowered island-wide total pumpage.

Historic pumping stresses are to be imposed to the model after initial water levels hav been calibrated. Ideally, there should be periods where recharge, pumping and water level show a steady-state like condition. This would allow the calibration of the model based on tw (2) apparent steady-state conditions where effects of storage depletion from an aquifer have con pleted and can be ignored (i.e. the effective storage coefficient can be set to zero (0) and it unnecessary to calibrate this parameter). Assuming the modeled long-term average recharge steady-state, one can identify the second situation by comparing pumpage and water levels alon However, no clear steady-state condition can be identified for all wells simultaneously. Thus, tl lack of two (2) definite steady-state situations island-wide makes it necessary to investigate tra sient situations to further evaluate the model. This entails calibration of the storage coefficie Therefore, periods where significant trend changes in related rainfall, pumpage, and water level were identified and resulted in eight distinct periods as shown in Figure 31, pg. 65. These san periods which define variations in pumping also define variations in recorded rainfall which c then be applied to the GIS recharge model to arrive at corresponding variations of recharge.

## Selection of Numerical Code for Model

The numerical model chosen for the flow model is the three-dimensional flow finite-difference model MODFLOW (McDonald, & others, 1988). The code is public domain, well documented, and is referenced herein. An additional package to the original MODFLOW was used to simulate the barriers to horizontal-flow imposed by dikes and faults (Hsieh, & others, 1993). This augmentative code is also an open file report with the USGS and well documented. The advantage of Hsieh's work is that the MODFLOW model grid need not be changed to add these barriers. Additionally, the MODFLOW code contains error checking criterion for calculated water levels and mass balance (water-budget within MODFLOW separate from the GIS water-budget).

The experience associated with MODFLOW's use was a major factor in selecting it for this preliminary model. MODFLOW has been the most widely used code by the USGS in modelling ground-water. One-hundred and sixty-five (165) calibrated models have been published by the USGS (Appel, 1994). There are other numerical models which are available but their use has been limited. For example, SHARP (Essaid, 1990) is a freshwater and saltwater flow model which could be used for Lana'i. However, there are limitations in its grid construction when compared to MODFLOW and it is usually used in areas where the interface near the shoreline is of importance. Additionally, SHARP is a quasi-three-dimensional model rather than the fully three-dimensional MODFLOW. Since the high-level ground-water source is of primary concern and not the shoreline interface between fresh and salt water, and it is a fully three-dimensional model, MODFLOW is considered the more efficient and appropriate model to use. Additionally, SHARP has only eight (8) documented calibrated models (Appel, 1994) as compared to MODFLOW's 165.

Basically, MODFLOW solves for the fundamental three-dimensional (3D) movement of ground-water by the partial differential Equation eq.(11), which is defined as:

$$\frac{d}{dx}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{d}{dy}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{d}{dz}\left(K_z\frac{\partial h}{\partial z}\right) = S_s\frac{\partial h}{\partial t}-F \qquad \text{eq.(11)}$$

where:

$K_x$, $K_y$, and $K_z$ = hydraulic conductivity along the x, y, and z axes (L/t)
$h$ = potentiometric head (L)
$F$ = net volumetric flux per unit volume of aquifer per unit time (1/t)
$S_s$ = Specific storage of porous material (1/L)
$t$ = time (t)

Equation eq.(11) is derived by combining Darci's law, equation eq.(1), pg. 14, and continuity considerations for a constant density fluid where flow into and out of the system is equal. Anderson (& others 1992) describes this fundamental equation as the flow system viewpoint where one is not concerned with identifying individual aquifers and confining beds *per se* but in constructing the 3D distribution of heads, hydraulic conductivities, and storage properties everywhere in the 3D system. MODFLOW's finite difference equations and numerical methods used to solve Equation eq.(11) between each cell is too technical for this report but is well documented.

# Numerical Model Construction

The goal of any numerical model construction is to represent the conceptual model prop erties of the study area in mathematical terms which can be solved numerically. To do this on requires the governing mathematical equations, or equation eq.(11), pg. 67, mathematical bound ary conditions, and known initial conditions. In constructing the Lana'i numerical model on concept was kept in mind at all times; make the model as simple as possible. Although this limi the flexibility of the model, this approach is thought to lend itself to easier model construction an calibration which is important in the initial interpretive phases of model construction. This als limits the "subjectivity" of the model by forcing the modeler to use one consistent approach.

## Grid

Before addressing the mathematical boundary conditions for the Lana'i numerical mod the grid, or discretization, for the model was made. This was due to the fact that the entire islan is modelled and external boundaries need not be critically examined as much in the initial discre ization phase. The simplest grid to construct is where individual cells are of uniform size whic adequately cover the entire area of interest. Since the model is at a regional scale cells should b on the order of many hundreds, or a few thousands, of feet square. A cell size of 2000 ft. by 200 ft. square, which covers an area of 1/4 $mi^2$, was arbitrarily chosen. This resulted in a total gri size of 1800 cells (50 x 36) which encompasses the entire island of Lana'i (See Figure 32). Fo convenience, the grid was oriented along the relatively straight northeastern coast of Lana' which spans from the mouth of Maunalei Gulch to Halepalaoa Landing, and such that wells we located in separate cells. The total grid size places the model in the regional scale catego according to Anderson (& others, 1992). This is an important feature since many different loc or site characteristics that may reside solely within one cell will be lost in the representati regionally effective characteristics.

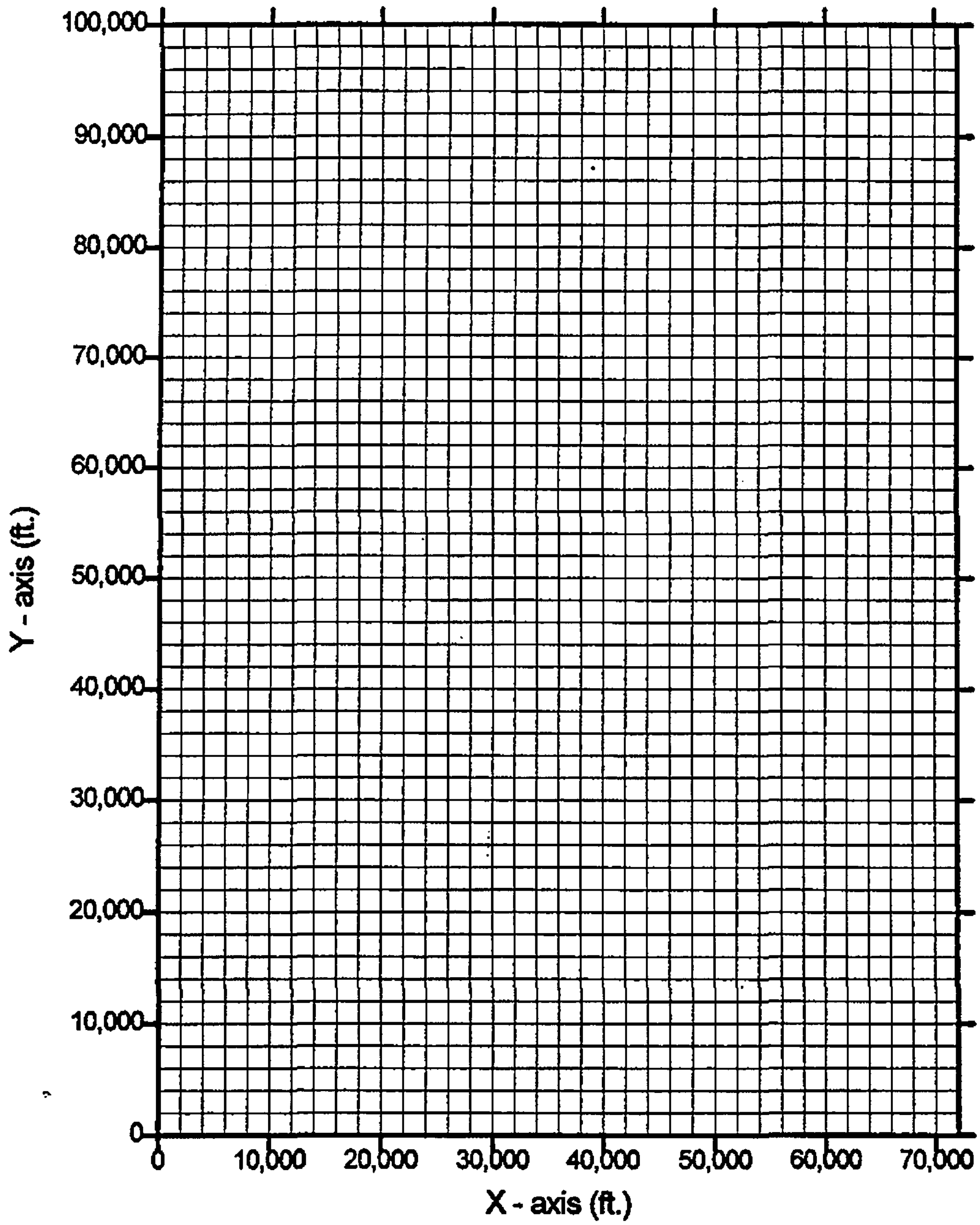
Grids in MODFLOW are finite difference which can be either block-centered or mes centered. Block-centered grids places the flux boundaries at the edge of the cells and the node the cell at the center, whereas the mesh-centered grid places the flux boundary at the nodes ar not the cell edges. To utilize the horizontal-flow barrier (HFB) package of MODFLOW t block-centered grid was chosen to use cell edges as flux boundaries.

## 2-D Rational

As shown in Figure 32, pg. 69, the model is only a single layer which effectively mak the Lana'i numerical model two-dimensional (2D). This is because for a single unconfined lay MODFLOW incorporates Dupuit assumptions which ensure horizontal-flow by requiring change in head with depth. This effectively removes the $K_z$ term, or any vertical flow, from equ tion eq.(11), pg. 67 and reduces the problem to one of 2D. However, MODFLOW can still sol 3D distribution of heads but multiple layers are necessary. Since the initial assumption was that the regional island scale the aquifer would behave isotropically and the model is preliminary, mu tiple layers are not necessary.

# Lanai MODFLOW 36 x 50 Grid

## 1800 Cells 2000 ft. x 2000 ft. square




Note: Y - axis in MODFLOW has origin at the top rather than the normal cartesian display as shown.

Figure 32. Single Layer MODFLOW Grid 50 x 36 Mesh with 2000 ft. square cells.

## Mathematical Boundary, Internal, & Source/Sink Conditions

The way the conceptual hydrologic boundaries and stresses correspond to the mathema cal boundary, internal, and source/sink conditions in the Lana'i numerical model are described the following paragraphs. It is important to note that setting boundary conditions is the step numerical modelling most subject to serious error (Franke, & others, 1987). It is believed that t assumptions of simplicity and uniformity made for the mathematical boundary conditions, int nal conditions, and source/sink terms will not induce serious errors.

Normally, when speaking of boundary conditions in a numerical model the modeler addressing the mathematical boundary conditions which define the extent or domain of the ent modelled area. These can be thought of as the perimeter, bottom, and top of the saturat ground-water between which all flow occurs within the grid layer. When these mathemati boundary conditions are specified then one may solve the partial differential ground-water fl equation eq.(11), pg. 67 through simultaneous algebraic equations in the numerical mo (Franke, & others, 1984). The three (3) major types of mathematical boundary conditions are:

(1) *Specified head;*

(2) *Specified flow; or*

(3) *Head-dependent flow* (some combination of (1) & (2)).

Such boundaries constrain the problem and make solutions unique. The freshwater fl at the coast does not extend for any significant distance offshore. Therefore, the edges of the g located in the ocean surrounding the island act as a *specified flow* type of no-flow boundar Also, the bottom of the freshwater lens is assumed to be an idealized constant which is not phy cally correct in location but is correct in establishing streamlines along the bottom of the aquif These streamlines go towards to ocean and provide a datum for the model to estimate aquife values based on given ***K*** values. This *specified flow* boundary of no-flow across the bottom of t model was set at -400 ft. msl based on geophysical resistivity work by Swartz (1940) which id tified the depth of salt-water/freshwater break in a cross-section of the island. As stated earli the maximum lens bottom estimate of -948 ft. msl at one station. Since the lens depth m decrease to approximately zero at the coast, the average between the coastline and the maxim lens depth was considered to be a reasonable assignment for the assumption of a constant bott depth ((948+0)/2 = 424 ≈ 400 ft.).

It is clear that the perimeter and bottom of the grid layer for the Lana'i model are no-fl mathematical boundaries. The top of the model, or the water table, is a different matter. Since Lana'i numerical model uses Dupuit assumptions, where all flow is horizontal in the 2D sin layer representation, flux across the water table is treated as a source, lumped in the ***F*** term equation eq.(11), pg. 67, rather than a boundary condition (Anderson, & others 1992). The governing numerical model mathematics, equation eq.(11), pg. 67, is such that if flux, the const ***F*** in the equation, were to also vary with time the solution would be non-unique and unsolva (Anderson, & others, 1992). Therefore, recharge flux is more appropriately handled throug separate water-budget analysis which was covered earlier in this report. Thus, the model's ma ematical boundaries are no-flow on five (5) of the six (6) edges of the grid layer.

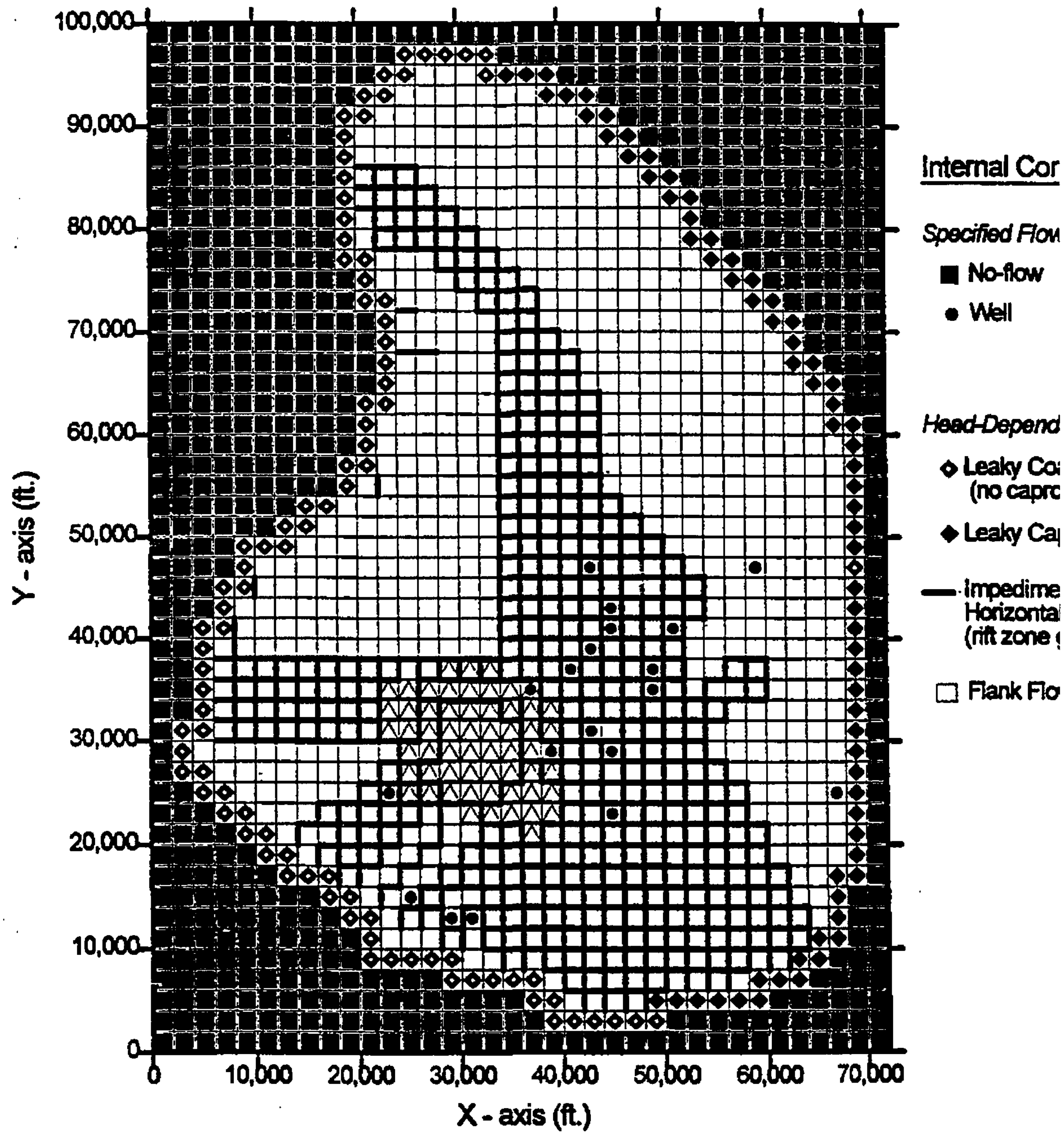
Internal conditions of a model are often confused with mathematical boundary conditions. The relevant physical or hydraulic hydrologic boundaries for Lana'i are the Pacific Ocean coastline which surrounds the entire island, a northern region of low permeability along the coast, the three rift zones which are manifested by observed dike and fault boundaries, the water table (computed by MODFLOW), the tunnel sources, and even flank flows. In the Lana'i numerical model, these conceptual hydrologic boundaries are types of *internal conditions*, or boundaries, which are different than the mathematical boundary conditions described in the previous paragraphs.

The Pacific Ocean coastline is represented by surrounding the island with the equivalent of a leaky streambed which is an *internal head-dependent flow condition.* The river or drain packages in MODFLOW calculate aquifer heads necessary to simulate seepage from the aquifer to a surface water body with a constant stage. These packages are identical although the river package allows flow to and from the surface water body whereas the drain package allows flow only to the surface water body. The river package, RIV, was chosen over the drain package to allow for ocean intrusion at the coast. Normally, the river package is used to represent streams but can be used to represent the equivalent leaky type of boundary where flow through the coastal toe of the basal lens must occur. The ground-water must pass through a thin region near the shore which approximates the toe of a basal aquifer which does not extend past the shoreline for any great distances. Therefore, a thin band of this leaky *internal head-dependent flow condition* surrounds the entire island as is shown in Figure 33, pg. 72. A total of one hundred and sixty-four (164) cells were identified to form a single cell wide band around the island. All cells ocean side of this boundary are not part of the island ground-water system and were given the *internal specified flow condition* of no-flow. The internal river boundary is divided into the two (2) regimes of a flank flow permeable southern coast and a less permeable alluvial northern coast. The demarcation points for these two regimes are Palahinu Point and Naha, which corresponds to Stearns (1940) description of coastal alluvial deposits and is twice the length of Adams (& others, 1973) study regime for the alluvial beachrock on the northern coastline. This stretch of northern shoreline is assigned a lower hydraulic conductivity than the southern shore with the exception of Lae Hi Point which happens to be a basaltic outcrop. These internal conditions corresponding to a caprock like condition impact a total of seventy-two (72) cells in the numerical model and are also shown in Figure 33, pg. 72.

The boundaries associated with three (3) major rift zones for Lana'i are also *internal head-dependent flow conditions.* The combination of dikes, faults, and rock contained within Lanai's rift zones produce a honeycombed effect as these geologic features incise the flank flows of the island and intersect with each other within the major rift zones. The horizontal-flow barrier (HFB) package in MODFLOW provides and easy way to produce model these conditions. A total of eight hundred and seventy-five (875) cell walls were made into effective internal HFB conditions. It is important to remember that these internal conditions represent the net effects of many unseen geologic features and are not actual individual boundaries.

The Lower and Upper Maunalei Tunnels are modeled as *internal head-dependent flow condition* through the drain package. Finally, all other pumping wells are sink terms in the model. One important issue with wells is that although they are located in the model's individual cells they are only approximately located at the central node in each cell. In addition to this approximation, interpolation errors between the grid nodes in this regional numerical model may be as much as 10 ft. (Anderson, 1988).

# Lanai MODFLOW 36 x 50 Grid




Note: Y - axis in MODFLOW has origin at the top-left rather than the cartesian display as sho

Areal Extent of High-Level Aquifer as defined by cells surrounded by impediments to horizontal flow = 57.4 sq. r

Figure 33. Final Boundary Conditions for the Lana'i Numerical Model

Source/sink terms are basically the net flux, $F$, applied at each cell node in the model in accordance with equation eq.(11), pg. 67. The recharge, $R$, array portion of this net $F$ term is the result of the GIS water-budget model discussed earlier and is a source term. The individual cell value results were constructed by merging the GIS results with the model grid and inputting the results into the recharge package of MODFLOW. Recharge values were in inches/day over for each cell area in the model grid which produce a cell volumetric inflow rate. Once initial water levels have been calibrated then pumping stresses can be imposed easily for each well by using the well package of MODFLOW. Pumping stresses in the Lana'i numerical model are all sink terms which mean they take water out of the aquifer system.

## Hydraulic Parameters

Previous discussions of the governing hydraulic equations for Darci's Law, equation eq.(1), pg. 14, and transmissivity, equation eq.(2), pg. 15, are not repeated here. Before discussing additional and individual hydraulic parameters there it is again necessary to clarify a major concept regarding their values. As discussed earlier and in general, the many sources of error associated with aquifer pumping tests dictate that values obtained are not absolute nor necessarily accurate and are more appropriate for local conditions and individual well performance rather than island-wide regional hydraulic behavior. Thus, this actual heterogeneity in the real world cannot be entirely dismissed. However, these hydraulic tests for do provide a 'ballpark' starting point and reasonable range to begin the numerical flow model parameter estimation process for an assumed or 'effective' homogeneous situation which represents the heterogeneous situation. Thus, it is important not to label or confuse resulting 'effective' homogenous hydraulic parameters estimated by the numerical analysis with the 'actual' hydraulic parameters in the very heterogeneous real world. However, it should also be understood that rules governing the estimation of these 'effective' homogeneous parameters are not well defined (Smith, & others, 1993).

For the Lana'i numerical model there are four basic hydraulic parameters which are varied in the calibration process. These are the global flank flow horizontal hydraulic conductivity, or permeability, $K_h$, the coastal streambed conductance term, $SC$, the horizontal-flow barrier (HFB) hydraulic characteristic, $HYDCHR_{ii'}$, and the tunnel drain conductance term $DC$.

Global $K_h$ can be described as the average effective hydraulic conductivity in the flank flow lavas. The average $K_h$ from existing pumping test data is 18.3 ft/day(Table 13, pg. 50). As stated earlier, it is known that pumping tests occurred in the rift zone and actually encountered dike, fault, or both boundaries. The intrusive boundaries cause greater drawdown during a pump test than would otherwise be observed which results in lower computed $K_h$ values for flank flows. It is difficult to determine to what degree pump test $K_h$ values would increase to correct for boundary encounters but it would not be unreasonable to assume flank flow $K_h$ values are within the range of tens ($10^1$) to thousands ($10^3$) of feet per day. The $K_h$ value may be lower in the Palawai Caldera region than other parts of the island as evidenced by pump test results (see Table 13, pg. 50) but it is less than an order of one (1) magnitude.

Streambed conductance, *SC*, is defined in MODFLOW as:

$$SC = \frac{Klw}{m} \qquad \text{eq.}$$

where:

$SC$ = Streambed conductance ($L^2/t$)
$K$ = hydraulic conductivity (L/t)
$l$ = length of cell (L)
$w$ = width of cell (L)
$m$ = depth of stream bed layer (L)

In the numerical model, the length, *l*, and width, *w*, are constant for all cells, including coastal cells, at 2000 ft. which results in an area of 4,000,000 sq.ft. The depth and thickness of coastal streambed was defined by setting the bottom of the river bed at -10 ft. msl in the mo which is estimated to be the equivalent depth of freshwater leakage depth at the coastline. RIV package requires a constant water level to be maintained in the stream/ocean coastline it which is sea level, or 0.0 ft. msl. The resulting stream bed hydraulic conductivity, *K*, must be estimated. The overall the *SC* term is inherently empirical (McDonald, & others, 1988) must be calibrated. Given the lack of a caprock type formation along the southern coast, the s ambed hydraulic conductivity, *K*, in eq.(12), is set equal to flank flow $K_h$ of any particular cali tion run. Given the caprock or beachrock coastal geology along the northern shore, streambed hydraulic conductivity, *K*, in eq.(12) for each cell must be calibrated and will be lo than the flank flow $K_h$ of the same corresponding calibration run. Typical *K* values for o windward type caprock have been estimated to range between 0.1 to 0.08 ft/day (Yuen, 1994)

The horizontal-flow barrier (HFB) boundary package for MODFLOW requires a hyd lic characteristic input which is defined as:

$$HYDCHR_u = \frac{K_{hb}}{w} \qquad \text{eq.}$$

where:

$HYDCHR_u$= Unconfined aquifer HFB hydraulic characteristic (1/t)
$K_{hb}$ = hydraulic conductivity of the horizontal-flow barrier(L/t)
$w$ = width or thickness of horizontal-flow barrier (L)

Equation eq.(13) is valid for MODFLOW layer types defined as unconfined. It is s what empirical since one does not know the actual width or actual 'effective' width of a I Therefore, $HYDCHR_u$ was allowed to vary as needed to simulate water levels. Since we k that the $K_{hb}$ term must be lower than the global flank flow $K_h$ term, the *w* term could be a si cant portion of the width of the cell, or 2,000 ft., and the $K_{hb}$ term could be several orders of nitudes lower than $K_h$, the $HYDCHR_u$ term should be as low as $10^{-4}$ or less.

There is no general formulation presented in MODLFOW for the drain conductance term, ***DC***, like the other modeled hydraulic parameters. This is due to the difficulty in quantifying all the parameters which affect flow to a drain. Therefore, it is truly a lumped proportionality parameter. However, three (3) processes affecting drain flow are discussed in MODFLOW and are described through equation eq.(14) as follows:

$$DC = CF \cdot K_D \cdot WL \qquad \text{eq.(14)}$$

where:

$DC$ = Drain conductance (dimensionless)
$CF$ = head losses from convergent flow to the drain
$K_D$ = hydraulic conductivity or material around drain
$WL$ = head losses from flow through the drain wall openings, length, etc.

Like $SC$, $DC$ is empirical and perhaps even more so given the fact that turbulent flow losses are to be accounted for in this term. However, if one knows the flow to the drain then $DC$ can be calibrated for that flow. Fortunately, sufficient Maunalei tunnel flow data is available.

As a final note, the storage coefficient, $S$ (see equation eq.(3), pg. 16), is set to zero (0) in all initial tunnel flow and water level computer runs since we are calibrating to an assumed steady-state conditions. In transient situations it will be necessary calibrate $S$ to match transient water levels.

## Solution Techniques

Of the two basic solution techniques available in MODFLOW to solve the large matrices-which are developed in making a model, the Strongly Implicit Procedure Package (SIP) was used throughout the computer runs for this study. SIP utilizes backward difference approximation, or implicit difference formulation (Wang, & others, 1982), to solve the system of linear equations which approximate the analytical solution to equation eq.(11), pg. 67 for each cell. This technique is favored since it always numerically stable, i.e. errors introduced at any time diminish progressively at succeeding times. The specific technique is not covered here but is well documented in MODFLOW (McDonald, & others, 1988). An alternative solution technique called the slice successive over-relaxation (SSOR) is available but was not used.

## Numerical Parameters (closure, seed, acceleration, etc.)

Various numerical parameters were used for error checking and to help speed convergence of the model. The closure criteria was set at 0.001 ft. maximum absolute value of head change and was constant throughout all simulations. Seed factors were always calculated by MODFLOW. The acceleration factor used was generally one (1) although model estimation sensitivity during later simulations necessitated smaller positive values (down to 0.1) to smooth solution closure and speed convergence.

## Calibration Targets (tunnel flow, initial water levels, transient water levels)

Generally, steady-state, or equilibrium, calibration targets need solid definition for a meaningful calibration effort. The steady-state targets are those conditions under which ground water level variation will be minimized under normal long-term climactic conditions. Ideally many observation wells could be put in and ground-water levels recorded many years prior to any pumpage to establish some stead-state distribution of ground-water levels. In reality, wells are normally pumped immediately after they are drilled since the expenditure of monies for drilling was justified by the potential utility of supplying water needs in the first place. Thus, as wells are drilled and pumped sequentially in time a steady-state situation may be hard, if not impossible, to define.

Fortunately for Lana'i, there is a period of steady-state pumping and initial water levels Aquifer water levels for the first ground-water sources, the Lower and Upper Maunalei Tunnel are difficult to ascertain except that they are higher than the tunnel floors. These tunnels had been producing ground-water for at least twelve (12) years prior to the drilling of later sources and may have affected the later sources' water levels. However, this seemingly unfortunate circumstance actually provides a steady-state situation. The steady-state calibration target was identified as the established base flow from the tunnels and the corresponding water levels for Shafts 1 & 2 which were not pumped significantly during this period and serve as observation wells. Other than this scenario, there is no other definite period of constant water levels with constant recharge, pumping, and ground-water levels in the record.

The establishment of baseflow from both Maunalei tunnels is difficult given the historical record. Although Stearns stated that the Lower Maunalei Tunnel was 'driven' in 1911, data recordation for the tunnel flows did not begin until 1926. However, Lloyd (1975) stated that water development of the gulch began in 1923. Whatever is the actual case, the tunnels had at least twelve (12) years in which to deplete storage and reach base-flow or steady-state conditions. On Oahu, the maximum time to establish based flow conditions for the Waiahole Ditch tunnels was approximately seven (7) years from Takasaki's (& others 1895) estimation of monotonic decay periods. Therefore, it is assumed that the Maunalei tunnels probably had reached steady-state base flow conditions before other Lana'i wells were drilled and pumped. Using this reasoning the average flow for the Maunalei tunnels during 1926 to 1939 was deemed to be an appropriate value to use. One could argue that perhaps the data from 1933 to 1939 would be an even better period of flow use since this would filter out the initial decay period of tunnel flow to get a better base flow average. However, considering the rainfall departure, as shown in Figure 10, pg. 23 & Figure 11, pg. 24, for the two different periods it can be seen that the 1933 to 1939 period is much wetter period than the longer 1926 to 1939 period. Not surprisingly, the average tunnel flow for 1933 to 1939 is slightly higher than the average flow for 1926 to 1933 for both tunnels. This indicates that the tunnel flows are sensitive to changes in climactic conditions and recharge. Therefore, the longer period was considered closer to the average climactic conditions on Lana'i than the 1933 to 1939 period and is somewhat more conservative. These tunnel flow calibration targets values are shown in Table 14, pg. 77. These target tunnel flows are primarily achieved by altering the ***DC*** parameter from equation eq.(14), pg. 75 but are also dependent on the inland ground-water levels which, in turn, are defined by the various other hydraulic parameters already defined.

As tunnel base flows are calibrated, observed ground-water levels for existing non-pumping wells or initial ground-water levels observed for wells drilled after the tunnels must also be calibrated. This results in a calibration effort which must simultaneously match tunnel base flows and initial ground-water levels in selected wells to achieve the calibrated steady-state situation. Ground-water level data from Shafts 1 & 2 provide the best estimate of initial water levels for the steady-state period, at least for the windward side of Lana'i. Although initial water level data is limited to these two (2) sources and not gathered on Lana'i under ideal conditions (windward only, and during a higher rainfall period), it is the best situation available for steady-state conditions. However, this situation can be helped by a ranking, or weighting, of other initial water levels encountered. The resulting ranking of initial water levels is more or less chronological since stresses imposed on the aquifer vary through time in concert with the construction of the wells. The calibration targets for initial water levels are shown in Table 14.

### Table 14. Calibration Targets and Rank of Importance

| Rank | Year Initially Drilled | Well Name | Well No. | Grid Location | | Initial Water Level (ft. msl) | 1926-1939 Average Q (mgd) |
|---|---|---|---|---|---|---|---|
| | | | | MODFLOW (row, col) | Plot x,y (1000 ft.) | | |
| 1 | 1900 | Gay Well A | 5149-01 | 38, 34 | 67, 25 | 2 | [a]na |
| 2 | 1911 | Lower Tunnel | 5053-01 | 32, 25 | 49, 37 | 1103 | 0.261 |
| 3 | 1911 | Upper Tunnel | 5053-02 | 33, 25 | 49, 35 | 1500 | 0.064 |
| 4 | 1918 | MH Tunnel | 4852-01 | 39, 24 | 47, 23 | (dry)<2700 | na |
| 5 | 1920 | Gay Tunnel | 4853-01 | 37, 22 | 43, 27 | (dry)<1920 | na |
| 6 | 1924 | Waiapaa Tunnel | 4952-01 | 36, 24 | 47, 29 | (dry)<2220 | na |
| 7 | 1936 | Shaft 1 | 5253-01 | 27, 30 | 59, 47 | 2.4 | na |
| 8 | 1938 | Shaft 2 | 5154-01 | 30, 26 | 51, 41 | 735 | [b]0.014 |
| 9 | 1945 | Well 1 | 4853-02 | 36, 20 | 39, 29 | 818 | 0 |
| 10 | 1946 | Well 2 | 4953-01 | 35, 22 | 43, 31 | 1544 | 0 |
| 11 | 1950 | Well 3 | 4954-01 | 32, 21 | 41, 37 | 1126 | 0 |
| 12 | 1950 | Well 4 | 4952-02 | 36, 23 | 45, 29 | 1589 | 0 |
| 13 | 1950 | Well 5 | 4852-02 | 39, 23 | 45, 23 | 1570 | 0 |
| 14 | 1950 | USGS T-3 | 5054-01 | 30, 23 | 45, 41 | 1067 | 0 |
| 15 | 1954 | Shaft 3 BH | 4953-02 | 35, 22 | 43, 31 | 1553 | 0 |
| 16 | 1986 | Well 6 | 5054-02 | 29, 23 | 45, 43 | 1005 | 0 |
| 17 | 1987 | Well 7 | 5055-01 | 27, 22 | 43, 47 | 650 | 0 |
| 18 | 1989 | Well 10 | 4555-01 | 38, 12 | 23, 25 | 208 | 0 |
| 19 | 1989 | Well 9 | 4854-01 | 33, 19 | 37, 35 | 808 | 0 |
| 20 | 1990 | Well 8 | 4954-02 | 31, 22 | 43, 39 | 1014 | 0 |
| 21 | 1990 | Well 12 | 4552-01 | 44, 16 | 31, 13 | 5 | 0 |
| 22 | 1990 | Well 13 | 4553-01 | 44, 15 | 29, 13 | 0 | 0 |
| 23 | na | Manele | 4454-01 | 43,13 | 25, 15 | [c]2 | 0 |
| 24 | 1950[d] | USGS T-2 | 4852-03 | [b]39, 23 | [b]45, 23 | na | 0 |

a. not available
b. based on 9/22/36 to 1/14/37 intermittent pump test (Stearns, 1940). However, ignored in calibration effort.
c. measured in 1993 when discovered by Lanai Co.
d. estimated.

It should be clear that no true "initial" ground-water levels, even in areas with zero pumpage, can be established without an initial comprehensive network of observation we Ground-water levels throughout the island will fluctuate naturally under varying climactic con tions, especially in dike confined regions. However, such variations in water levels sho approach an average equilibrium over time periods where long-term natural conditions can identified. Unfortunately, observation well networks are seldom in place prior to pumping con tions and Lanai's situation is no different. Since pumpage would affect initial regional equil rium ground-water levels, then the earliest drilled wells deserve greater weight in matching tl wells drilled later in time. Additionally, although tunnels do not give an accurate measure of ground-water table other than the fact that they lie below it (or above it if dry!), they do prov limits which must be met. Also, geothermal heating for Wells 1, 9, and 10 affects the water lev initially encountered. Such heating could account for water level differences in the neighborhc of five (5) feet differences for these three wells (this can easily be calculated by taking specific ratio of water's approximate specific weight at 60° F and 100° F, or 62.37/62.00 (Roberson. others, 1980), multiplied by a 1' x 1' x 900' water column = 5.4 ft). Therefore, the initial grou water levels should not be affected by geothermal activity significantly in areas with water lev exceeding several hundreds of feet in elevation on Lana'i.

In addition to the steady-state calibration targets, levels or associated error targets mus defined to provide an additional basis of identifying an acceptably calibrated solution. Given model assumptions of regional isotropy, homogeneity, and other averaged hydrologic paramet it is unlikely that every observed water level will match perfectly. Associated error targets p vide a means of a qualifying how well the steady-state calibration targets have been achieved ative to one another. For this study, an acceptable steady-state calibration solution is achie when the combination of all model hydraulic parameters resulting in observed tunnel flows water levels minimize the associated errors. This was accomplished most efficiently by defin several levels calibration and striving to maximize higher levels of matching while minimiz lower levels of matching. Therefore, such associated error targets are defined for both Maun Tunnel base flows and initial water levels in which is summarized in Table 15.

**Table 15. Levels of Calibration for Lana'i Numerical Model**

| Level of Calibration Simulated vs. Observed Water Levels | Associated Error | | |
|---|---|---|---|
| | Aquifer Type | | Maunalei Tunnels Base Flow 1926-1939 (%) |
| | Dike-Confined (ft.) | Basal (ft.) | |
| 1 | 30 | 1 | 5 |
| 2 | 60 | 2 | 10 |
| 3 | 90 | 3 | 15 |
| 4 | > 90 | > 3 | 20 |

Admittedly, levels of associated error targets are subjective but are based on relevant criteria. Typical flow meters and totalizers, especially older, are commonly known vary as much as 5%. Given the uncertainty of the tunnel base flow data and the completeness of their record variability is arbitrarily set in increments of 5%. For water levels, properly installed airline measurements are accurate to the nearest 0.1 ft. Also, and as mentioned earlier, nodal interpolation errors alone may cause errors up 10 ft. in a regional model (Anderson, & others 1992) and well locations are not exactly coincident with nodal locations in the grid. The ignorance of return irrigation could also affect water levels but such effects are probably limited to the Palawai basin area. Also, dike-confined water levels are generally more sensitive to climactic variations than basal aquifers. Since the majority of wells on Lana'i are located in dike-confined regions their initial water levels will be difficult to match due to local climactic differences when initially drilled. As described earlier, geothermal presence can also affect water levels by a few feet in the Palawai Caldera. Considering these factors alone would justify an associated error of several tens of feet. Basal wells, on the other hand, typically do not exhibit the same level of sensitivity to climactic and pumping stresses. Therefore, the associated error for basal wells should be much lower than that for dike-confined water levels; on the order of a few feet. Again, these associated errors are subjective and based on discussions with hydrologists of the USGS, CWRM, and LCo.

There are two (2) additional calibration targets which must be met before any of the initial water level or tunnel base flow results are compared to the calibration targets identified in Table 14, pg. 77 and Table 15, pg. 78. These are the water level closure criteria, where the numerical iteration processes will stop, and the corresponding mass balance for each run. A rule of thumb is that simulated water level closure criteria should be one to two orders of magnitude smaller than the level of accuracy possible (Anderson, & others, 1992). Since water levels have been measured to the nearest 0.1 ft. on Lana'i this would correspond to a closure criteria of 0.001 ft. Each calibration run had to meet this error criterion, which means that before its results were accepted, water level changes between progressive iterative solutions for each cell could not exceed this amount. The mass balance error is calculated by MODFLOW at the end of a calibration run when the water level closure criteria is met. A mass balance target error of 1%, or less, is considered acceptable (Anderson, & others, 1992). When both these error criterions were met the results of a calibration run were considered acceptable to rate against Tables 14 & 15.

A second major effort in this calibration process was to match transient water levels in each well with historical data. The target transient ground-water levels are defined as those observed in each well over the eight periods identified in Figure 31, pg. 65. The effort here is to calibrate the model's effective storage coefficient, *S* (see equation eq.(3), pg. 16), and also to give a sense of reliability to the initial steady-state calibration effort. As stated previously, the reasonable range of *S* is 0.1 to 0.3 for the unconfined aquifers. Other modelling studies in the State, on the island of Oahu, have shown that storage coefficients between 0.02 to 0.05 appear reasonable for unconfined basal situations (Eyre, & others, 1986). Whether or not this is the case for high-level unconfined aquifers is subject to conjecture. In any case, it is much more difficult to identify a *S* calibration or an associated error target with water levels since they vary with time. Instead, transient water levels were analyzed in a more spatial context at each well site. This spatial analysis also provided insight for changing boundary conditions. For example, it was found during early rounds of the transient simulations that the windward water levels were reacting too low while the leeward side water levels were reacting too high. This lead to a change in the configuration of dike boundaries on the windward side which led to a better match in transient water level response.

# Model Calibration Results

Trial-and-error is the method used to arrive at best fit solutions for initial steady-state a transient recharge and pumping water levels. In both situations, the goal is to meet the associa error and closure criteria conditions which minimize the average difference between the sin lated and observed initial heads and pumping drawdowns. MODFLOW does have an automa calibration module called MODFLOWP. However, MODFLOWP is a recent code which has been used much and it may be 10 to 20 years before the use of such automatic calibration mod become standard practice (Anderson, & others, 1992). Therefore, this study remained with trial-and-error method of calibration. It is important to understand that the trial-and-er approach does not guarantee the statistically best solution (Anderson, & others, 1992). Therefc sensitivity analysis will be necessary later to quantify the uncertainty of the parameter estimat through this trial-and-error approach.

There are many ways to identify and measure the success of the calibration effort Lana'i. The two (2) major categories to evaluate the calibration effort are *quantitative* and *qu tative* measures of success. The ultimate calibration objective is to minimize both types of m sures of error. The statistical measures used in this study to *quantify* average differences betw the simulated and observed initial heads and transient drawdowns are the mean error (**ME**), mean absolute error (**MAE**), and the root mean squared error (**RMS**), or standard deviati However, these *quantitative* statistical properties do not identify the spatial, or *qualitative*, dis bution of the errors. Therefore, spatial relationships between simulated and observed water le must be shown graphically as well.

## Initial Steady-State Ground-Water Levels

Over a thousand (1000) ground-water level simulation runs were performed to calib the model to the initial steady-state water level conditions. In the effort to verify the final conc tual model, many of these runs were made to test possible conceptual models which were m simpler but probably too simple to meet observed conditions. For example, through many co puter runs it was found impossible to match observed water levels with a single uniform effec global permeability, $K_h$, devoid of other internal boundaries to horizontal-flow, with a calibra level of 1 (see Table 15, pg. 78) for more than 1 well at any time. Likewise, it was found im sible to match observed water levels by using only field identified dike and fault and bounda alone without any inference of unseen horizontal-flow boundaries which must exist in the kn rift zones. Thus, the failure of these simpler conceptual models mean that they are too simple that there must be many unseen internal boundaries. Some adjustments to internal boundary ditions were necessary in the rift zones and along the shoreline to calibrate the model but ov there is little deviation from the initial assumptions of homogeneity, isotropy, and simplicity the regional scale of the Lana'i numerical model. Therefore, many of the earlier simulation were used as rule out other possible conceptual models.

Following the initial invalidation of oversimplified conceptual models, the final con tual model, as shown in Figure 33, pg. 72, was calibrated by varying the various hydraulic pa eters until a best fit match for the in initial steady-state water levels was obtained. MODFL input data and resulting output data for the best fit calibration are located in Appendix C and

Summaries of the best calibration fit to initial steady-state ground-water level conditions are shown in Tables 16 & 17 and Figures 33 and 35. It is important to understand that this is not a unique solution and that other combinations of these hydraulic parameters can result in similar results although changes in conceptual internal boundary conditions have a much greater effect on the quantification of these parameters. For example, it was found that under the original boundaries to horizontal-flow configuration initial water levels for Wells 1 and 12 were several hundred feet too high when other wells seemed to be reasonably matched. The solution for this was to remove the makai most boundary to horizontal-flow which solved the problem rather than trying to alter the hydraulic permeabilities locally. Likewise, using recharge distributions from past studies resulted in Shaft 2, the most important initial water level, drying up consistently when pumped at its long-term average, which is not consistent with reality. Only after the GIS recharge was overlaid on the model was the Shaft 2 problem resolved. An important feature of the steady-state calibration effort was that the Upper Maunalei Tunnel needed to cross into the next mauka cell since it was impossible to get enough flow out of one cell only. This is reasonable since the tunnel source is really horizontal and may indeed cross into another cell in the conceptual model. Whether or not this is true, such a change is necessary for the model to achieve the defined steady-state target conditions.

**Table 16. Resultant Calibration Parameters for Initial Steady-State Conditions**

| Parameter | Property | Value | unit |
|---|---|---|---|
| *S* | Storage Coefficient | 0 | dimensionless |
| $K_h$ (both x & y directions) | Global Horizontal Permeability | | |
| Island | | 1000 | ft/day |
| Palawai Caldera | | 100 | ft/day |
| *SC* | Coastal Leakance | | |
| Southern coast | | $4 \times 10^6$ | $ft^2/day$ |
| Northern coast | | $4 \times 10^4$ | $ft^2/day$ |
| $HYDCHR_u$ | Horizontal Flow Boundary Conductance | | |
| Dike Complexl | | $5.01 \times 10^{-5}$ | 1/day |
| *DC* | Drain Leakance | | |
| Lower Maunalei | | 255.84 | $ft^2/day$ |
| Upper Maunalei | | 1370.00 | $ft^2/day$ |
| Extension of upper | | 1370.00 | $ft^2/day$ |
| *R* | Recharge | 61.60 | mgd |
| Area of *R* | Recharge area | 140.83 | $mi^2$ |
| Bottom Elevation | Bottom of model | -400 | ft |
| Pumping | Pumpage scenario | 0 | mgd |
| **MODFLOW Calculations** | **Accepted Calibration Targets** | **Value** | **unit** |
| Mass Balance | values < 1.0% are acceptable | -0.05 | % |
| Closure Criteria | water level changes < 0.001 ft stops iteration | na | ft. |

## Table 17. Best Fit Steady-State Calibration Results

| Rank | Well Name | Initial Water Level (ft. msl) | Calibrated 1939 Water Level (ft. msl) | Δ | Level of Calibration | Discharge Q (mgd) |
|---|---|---|---|---|---|---|
| 1 | Gay Well A | 2 | 2.5 | +0.5 | 1 | 0 |
| *2 | Lower Tunnel | 1103 | 1240 | +137 | [a]1 | 0.261 |
| *3 | Upper Tunnel | 1500 | 1506 | +6 | [a]1 | 0.064 |
| *4 | MH Tunnel | (dry)<2700 | 1841 | [b]nn | 1 | 0 |
| *5 | Gay Tunnel | (dry)<1920 | 1504 | nn | 1 | 0 |
| *6 | Waiapaa Tunnel | (dry)<2220 | 1743 | nn | 1 | 0 |
| 7 | Shaft 1 | 2.4 | 2.4 | 0 | 1 | 0 |
| 8 | Shaft 2 | 735 | 738 | +3 | 1 | 0 |
| 9 | Well 1 | 818 | 850 | +32 | 2 | 0 |
| 10 | Well 2 | 1544 | 1523 | -21 | 1 | 0 |
| 11 | Well 3 | 1126 | 1154 | -28 | 1 | 0 |
| 12 | Well 4 | 1589 | 1625 | +36 | 2 | 0 |
| 13 | Well 5 | 1570 | 1723 | +153 | 4 | 0 |
| 14 | USGS T-3 | 1067 | 1131 | +64 | 3 | 0 |
| 15 | Shaft 3 BH | 1553 | 1523 | -14 | 1 | 0 |
| 16 | Well 6 | 1005 | 991 | -14 | 1 | 0 |
| 17 | Well 7 | 650 | 755 | +105 | 4 | 0 |
| 18 | Well 10 | 208 | 318 | +110 | 4 | 0 |
| 19 | Well 9 | 808 | 846 | +38 | 2 | 0 |
| 20 | Well 8 | 1014 | 1191 | +177 | 4 | 0 |
| 21 | Well 12 | 5 | 0.3 | -4.7 | 4 | 0 |
| 22 | Well 13 | 0 | 0.7 | +0.7 | 1 | 0 |
| 23 | Manele | [c]2 | 2.3 | +0.3 | 1 | 0 |
| *24 | USGS T-2 | [d]na | na | na | na | 0 |

a. steady-state flow equal to '26-'39 average.
b. not necessary
c. measured in 1993 when discovered by Lanai Co.
d. not available.

$$ME = \frac{1}{n}\Sigma(initial - calibrated) = -40.4$$

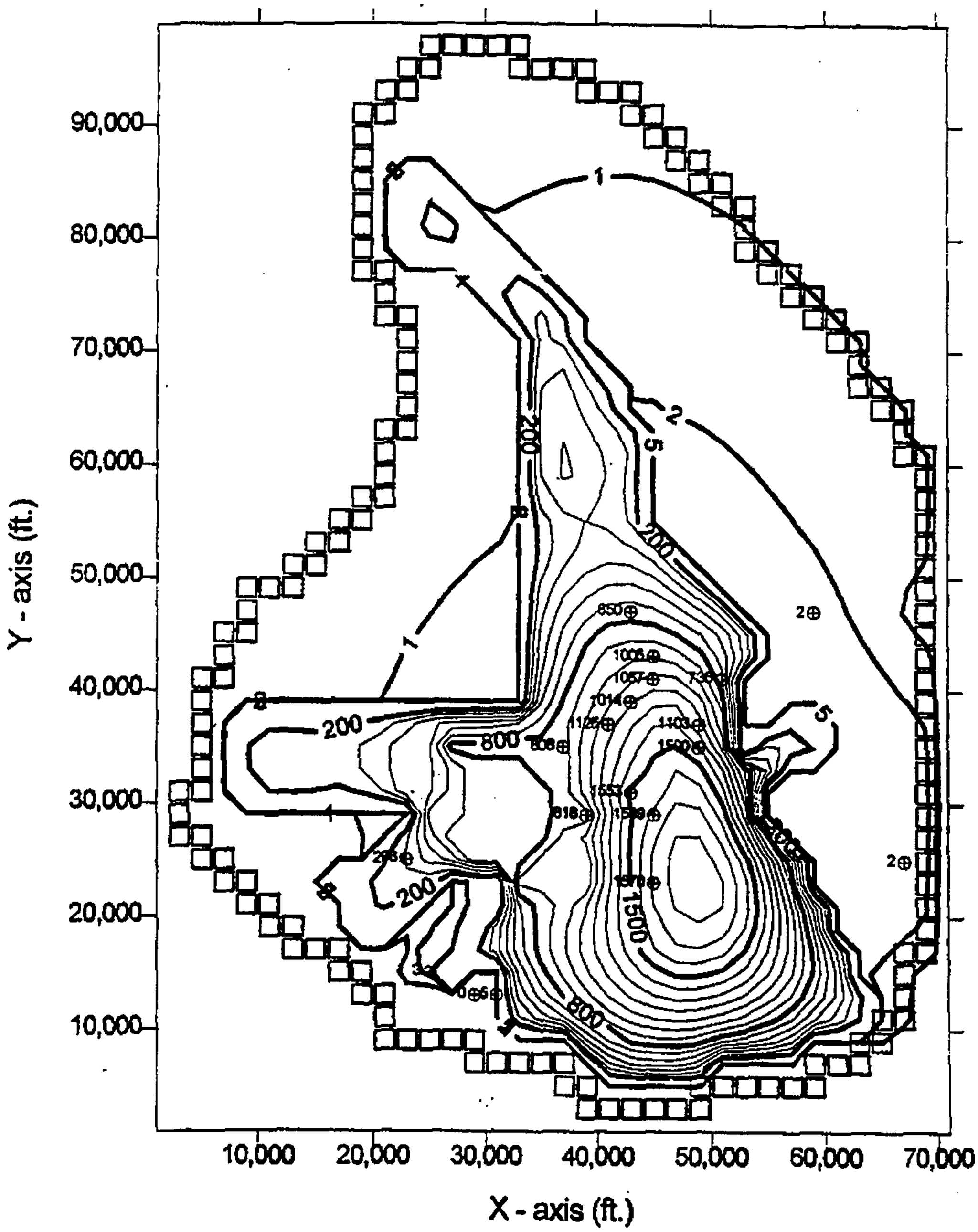
where $n = 18$ (wells marked * not counted)

$$MAE = \frac{1}{n}\Sigma(|initial - calibrated|) = 48.1$$

$$RMS = \left[\frac{1}{n}\Sigma(initial - calibrated)^2\right]^{0.5} = 72.3$$

# Simulated Regional Steady-State Ground Water Level Contours for Lanai

## Best-Fit Calibration with Fog-Drip




MODFLOW INPUT DATA

Storage Coeffcient. = 0 (i.e. non-transient)
Global Kh = 1000 ft/d
Caldera Kh = 100 ft/d
River conductance Klw/m
  with lw=4,000,000 sq.ft.,m=100 ft.,@ z=0 ft. msl
  where South K=1000 ft/day = 400,000,000 sq.ft./day
  where North K= 0:1 ft/day = 40,000 sq.ft./day
  and where river bottom = -10 msl.
Horizontal flow boundaries = 895
  Horizontal flow boundary conductance K/w = 0.0000501/day
Bottom elevation = -400 ft.
Area of recharge = 140.83 sq. mi.
Recharge = 61.60 mgd
Pumping = 0 mgd
Flow from Lower Maunalei Tunnel = 0.261 mgd
Flow from Upper Maunalei Tunnel = 0.064 mgd

MODFLOW OUPUT THROUGH SURFER GRAPHICS

Maximum water level = 1868 ft. above mean sea level.
(contour truncated at 1800 ft. above msl)

⊕ - Well locations with original water levels.

□ - Numerical coastline of Lanai

CLOSURE CRITERIA

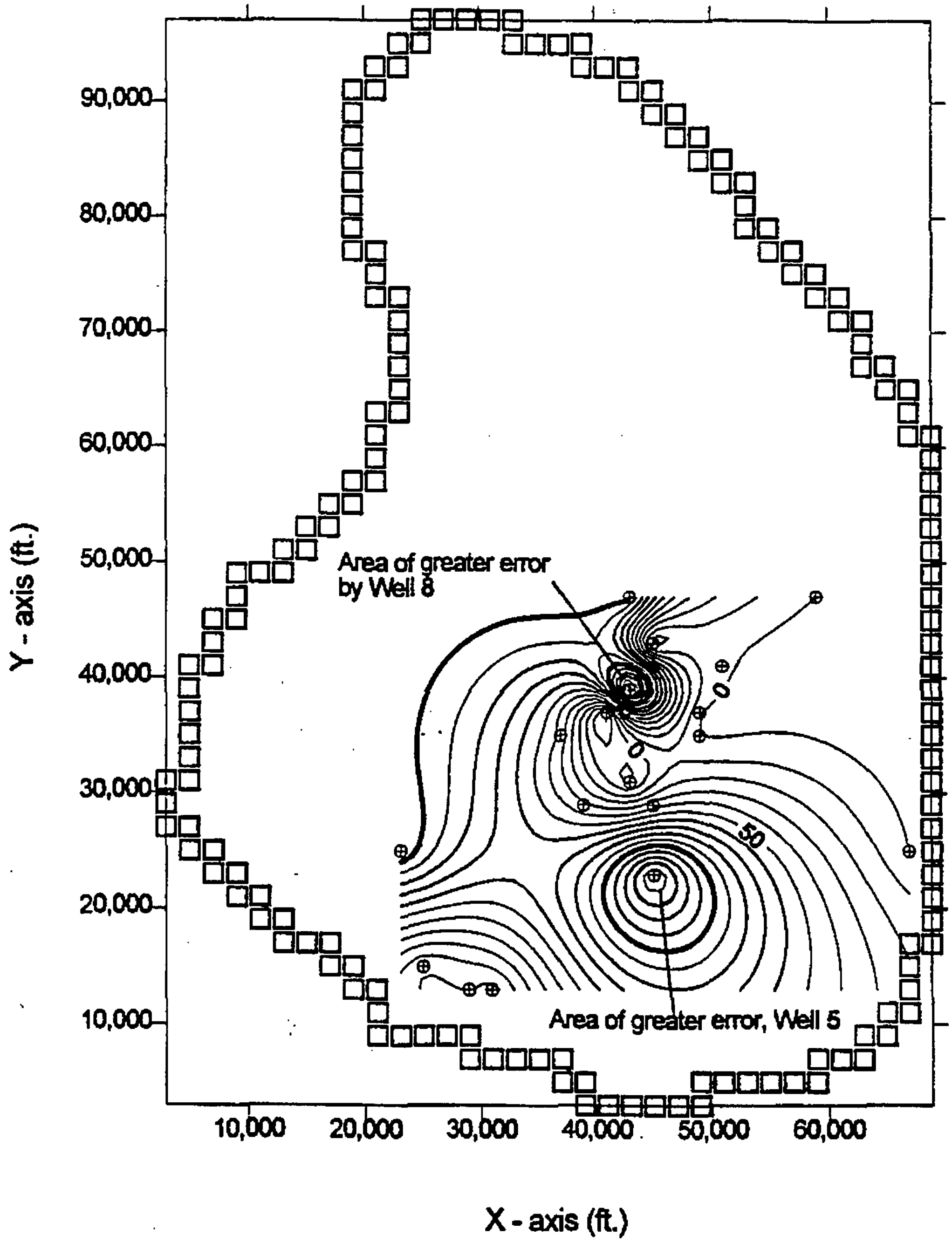
Maximum water level change < 0.001
Water balance < 1% (Actual = -0.05%)



Figure 34. Spatial Contour Results of Best Fit Calibration

# Simulated Regional Steady-State Drawdown Contours for Lanai

**Best-Fit Calibration Spatial Error Distribution**




MODFLOW OUPUT THROUGH SURFER GRAPHIC

Minimum error = -20 ft.
Maximum error = 160 ft.
Contour interval = 10 ft., Darkest contour line is +10

⊕ - Well locations with original water levels.

□ - Numerical Coastline of Lanai

Figure 35. Spatial Distribution of Errors for Best Fit Calibration

From Table 17, pg. 82, it can be seen that levels of calibration for the earliest sources match much better than later sources, which is expected. The MAE of the simulated water levels for all wells is 48 ft., which implies that the overall match is fair (Level 2, as defined in Table 15, pg. 78) while the standard deviation is 72 ft. (Level 3). However, considering the assumptions of homogeneity and isotropy and the transient considerations of wells coming on-line at various times, the match is better than expected. Additionally, calibrated hydraulic parameters from Table 16, pg. 81, fall within the range of reasonable values mentioned earlier in this report.

To investigate the reasonableness of the 61.60 mgd recharge ***R*** input, a separate calibration was performed where the fog-drip component of ***R*** was entirely removed. The total average ***R*** for this situation was 53.18 mgd (see Table 12, pg. 48). The same technique and closure criteria from the previous calibration was used. The best calibration fit parameter values with the no fog-drip ***R*** are summarized in Table 18 below.

**Table 18. Resultant Calibration Parameters for No-Fog Steady-State Conditions**

| Parameter | Property | Value | unit |
|---|---|---|---|
| *S* | Storage Coefficient | 0 | dimensionless |
| $K_h$ (both x & y directions) | Global Horizontal Permeability | | |
| Island | | 1000 | ft/day |
| Palawai Caldera | | 100 | ft/day |
| *SC* | Coastal Leakance | | |
| Southern coast | | $4 \times 10^8$ | $ft^2$/day |
| Northern coast | | $4 \times 10^4$ | $ft^2$/day |
| $HYDCHR_u$ | Horizontal Flow Boundary Conductance | | |
| Dike Complex | | $2.40 \times 10^{-5}$ | 1/day |
| *DC* | Drain Leakance | | |
| Lower Maunalei | | 5120.00 | $ft^2$/day |
| Upper Maunalei | | 5120.00 | $ft^2$/day |
| Extension of upper | | 5120.00 | $ft^2$/day |
| *R* | Recharge | 53.18 | mgd |
| Area of *R* | Recharge area | 140.83 | $mi^2$ |
| Bottom Elevation | Bottom of model | -400 | ft |
| Pumping | Pumpage scenario | 0 | mgd |
| **MODFLOW Calculations** | **Accepted Calibration Targets** | **Value** | **unit** |
| Mass Balance | values < 1.0% are acceptable | -0.05 | % |
| Closure Criteria | water level changes < 0.001 ft stops iteration | na | ft. |

As expected, the ***HYDCHR***$_u$ and ***DC*** terms were different in the no fog-drip ***R*** scenario. The best way to compare the impacts of these changes is to view the changes in the profile of the resulting changes in water levels (see Figures 36 & 37 on the following pages).

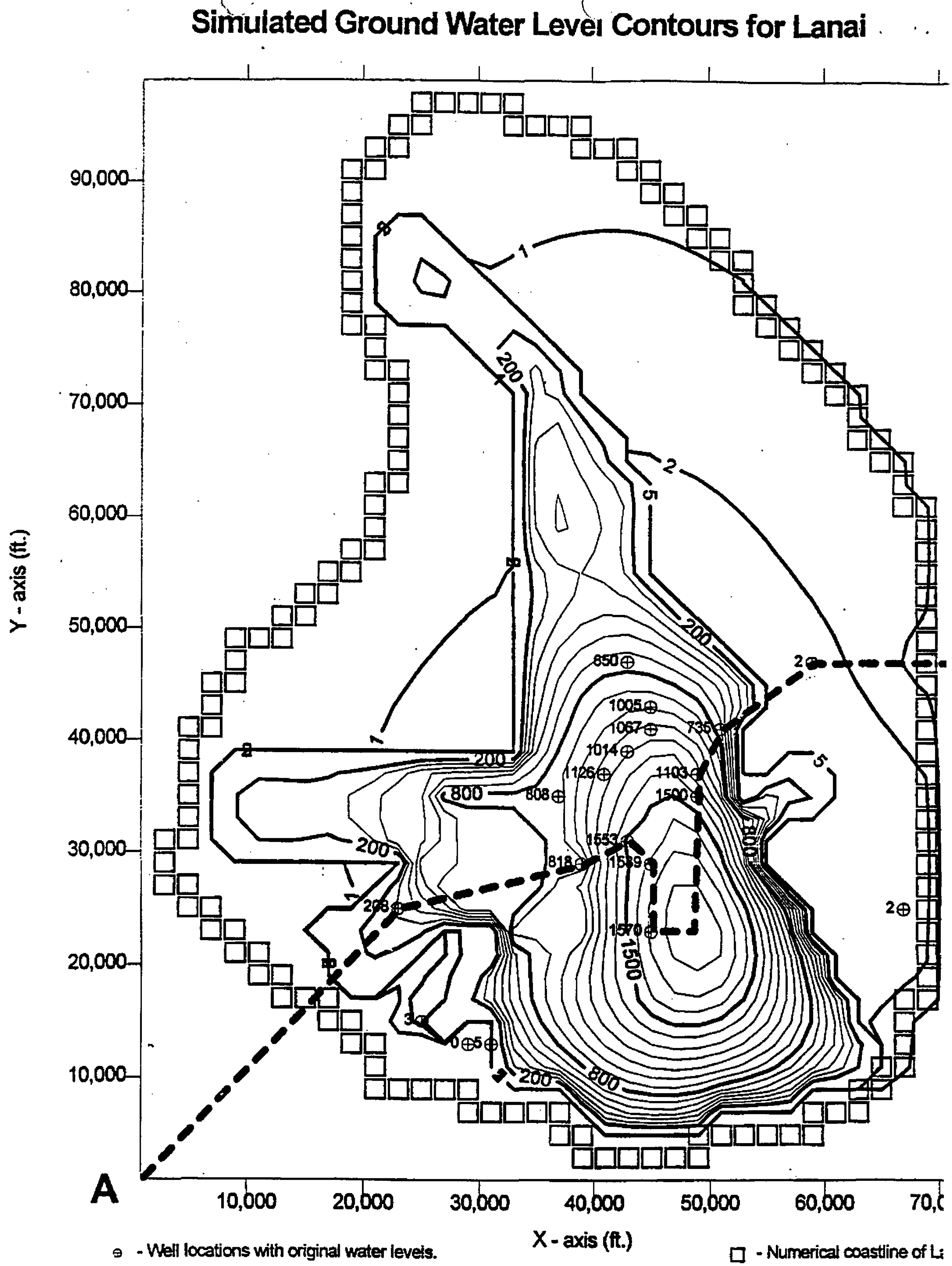



Figure 36. Profile Line A-A' Superimposed on Ground-Water Level Contours

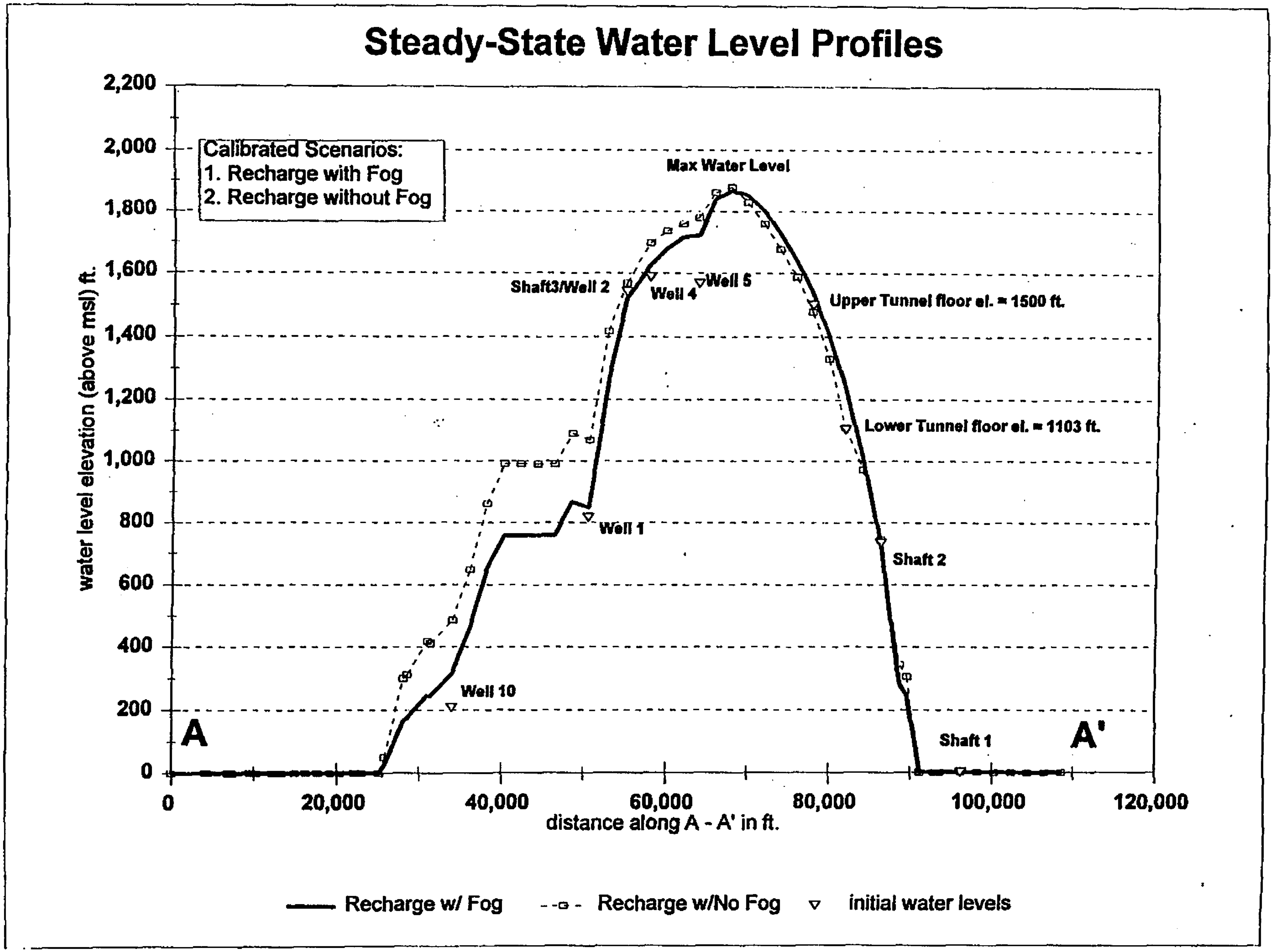



Figure 37. Resulting Profile A-A' Differences from Fog vs. No Fog Recharge Calibration.

The results of this alternative calibration show that, for the given conceptual model w: all its assumptions and identical internal boundary locations, the ***R*** with ***FD*** is a better estimate island ***R*** than without ***FD***, for several reasons. First, it was impossible to get the Upper Mauna. Tunnel to flow at all under the same steady-state model conditions as the previous calibration. was found that additional 2000 ft. mauka extensions to *both* tunnels was necessary to achieve t calibration target of historic tunnel flows observed, before any other wells were drilled, for without ***FD***. These boundary changes are not incorporated into Figure 37, pg. 87 since we a comparing calibrations without boundary changes which is a more meaningful compariso Therefore, it was only possible to match the Lower Maunalei Tunnel flow and initial Shaft 2 wa levels but not the Upper Maunalei Tunnel flow. This is clearly visible in Figure 37, pg. 87 sin the Upper Maunalei Tunnel will not flow in the ***R*** without ***FD*** scenario since the bottom of t tunnel floor lies above the ground-water level. Even if these boundary changes were allowed t horizontal flow boundary, $\boldsymbol{HYDCHR_u}$ had to be decreased such that ground-water levels cou rise to achieve not only tunnel flow but the observed initial water level at Shaft 2.

The fact that $\boldsymbol{HYDCHR_u}$ must be decreased (tightened) to meet the calibration targets expected, since less recharge would require tighter dike and fault formations to increase wa levels to compensate for less ***R***, and is the second reason why ***R*** with ***FD*** is a better estimate island ***R*** than without ***FD***. Removing ***FD*** from ***R*** affects water levels on the leeward side mo than the windward side of the island. For ***R*** without ***FD***, calibrated water levels on the leewa side of the island are consistently higher than if ***R*** incorporates ***FD***, as is clearly shown in Figu 37, pg. 87. All the observed initial high-level water levels with a calibration level greater thar are already lower than water levels from the calibration with ***R*** containing ***FD*** (see Table 15, p 78 and Table 17, pg. 82). Therefore, removing ***FD*** from ***R*** increases this error rather th decreasing it.

Lastly, the decrease in $\boldsymbol{HYDCHR_u}$ will also affect aquifer response to long-term avera pumpage such that drawdowns for the model calibrated without ***FD*** are less reasonable. Figu 38, pg. 89 shows that even with long-term pumping the water levels at Wells 1 and 10 are on t order of 200 to 300 ft higher than what has been initially observed at these two wells sites. Al drawdowns in other wells seem much more drastic than what is observed in the field. From F ure 38, pg. 89 it can be seen that the drawdowns at Wells 2 & 4 should be on the order of 300 600 ft greater than what is currently observed and historical behavior of these sources do not in cate that such drawdowns would be expected. The only exception of ground-water level respo without ***FD*** is Well 5, which appears to be a better match than the calibration with ***FD***. Howev Well 5 is known to have efficiency problems and, as will be seen later in transient runs, this sou is one of the more poorly modeled wells in this report. Therefore, it is the opinion of the autl that this figure is further evidence that the model calibrated with ***FD*** is a better calibration tl without it. Therefore, calibration parameters made with ***FD***, as described in Table 16, pg. 81 deemed the "best-fit" calibration model from here on in this report.

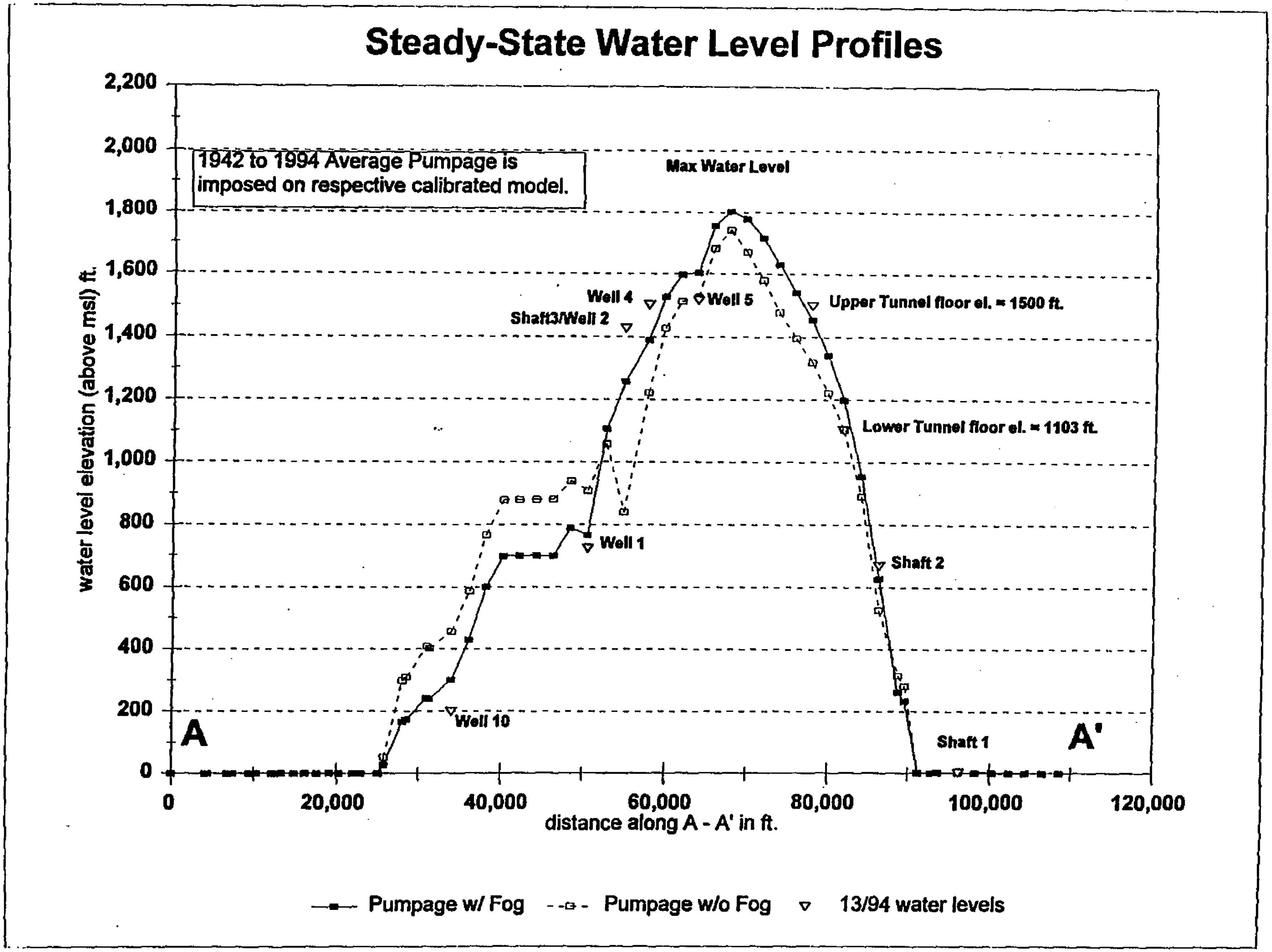



Figure 38. Resulting Profile A-A' Differences in Long-Term Pumpage Results on *FD* vs. *NO-FD* Calibrations

# Transient Recharge, Pumping, and Water Levels

Following the steady-state initial water level calibration, transient water levels are investi gated to calibrate the effective storage coefficient *S* and to further provide confidence in the cali bration of the steady-state conditions. As shown from Figure 31, pg. 65, there are eight (8 periods of significant changes in static water level trends from 1942 to 1994. These periods corre spond to what are called stress periods in the numerical model. Therefore, there are eight (8 stress periods in the transient model input. Since the high-level water elevations are sensitive t both climactic and pumping stresses both must be varied within the defined periods.

Varying recharge, ***R*** (with fog-drip, ***FD***), over the specified periods was accomplishe through the GIS by applying the monthly departure from the long-term monthly means for rair fall, ***RF***, and running the recharge model with these modified ***RF*** variables for each period. N other water-budget parameters were altered and it is assumed that the lag-time between recharg and water levels is negligible. The results for the periodic ***RF*** departure computations are show in Table 19, pg. 91. The resulting effect on the GIS ***R*** departure computations for each stres period are shown in Table 20, pg. 91, and it is interesting to note that they generally exceed ***R*** departures. The reason for the difference in departures is most likely due to the differences i $ET_m$ which is dependent on changes in soil-moisture storage, $\Delta SMS_m$, which was discussed ea lier in this report. Computations of periodic recharge rates used in deriving the tables 19& 20 ca be found in Appendix E.

Of the twenty-four (24) ground-water sources identified for Lana'i in this report, onl eleven (11) of these were pumped significantly and of these eleven only nine (9) have water lev responses to pumpage and climactic changes. These production wells and their correspondin average pumpage for each period are summarized in Table 21, pg. 92. Yearly time-steps we investigated for each stress period. For example, in stress period one, '42 to '51, there are ten (1 years or ten (10) time-steps in the model. In each of these time-steps the model will iterate to solution which meets the criteria set forth in Table 16, pg. 81 before moving to the next time-ste However, since this is a transient simulation the water balance criteria does not have to necessa ily meet the steady-state condition of 0.05% difference since changes in storage now occur.

For comparison, specific capacities reported by Takasaki (& others 1982) for wells in t Waiahole-Waikane dike complex region range between 1 to 10 gal/min/ft which means that a w pumped at a rate of 200 gal/min would result in a drawdown of between 200 to 20 ft., respe tively. This is consitent with the current reaction of most individual wells pumpage on Lana'i.

With the transient input variations established, calibration of the storage coefficient, was approached by trial-and-error. Five (5) *S* values were investigated; 0.01, 0.05, 0.1, 0.2, C with the assumption of homogeneity on the island-wide regional scale. No lag-times were cc sidered. The resulting transient water level runs and tunnel flows for the final calibration a found in Appendix F. The best *S* value is the one which matches the trend or relative changes ground-water levels for each source. This is best accomplished by matching the departures fr the mean for each source for the observed data and each resulting simulated transient run. The results are graphed in Appendix F.

## Table 19. Stress Period Departures from Mean *RF* for *R* Calculations

| Month | Departure from Monthly Mean Rainfall, *RF* in % | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Period 1 '42-'51 | Period 2 '52-'56 | Period 3 '57-8/61 | Period 4 9/61-'64 | Period 5 '65-'69 | Period 6 '70-'83 | Period 7 '84-'90 | Period 8 '91-'94 |
| Jan | 14.77 | -13.10 | 3.13 | 77.44 | 29.92 | 27.36 | -37.71 | -43.66 |
| Feb | -6.23 | -13.59 | -44.13 | -67.36 | 22.25 | 9.65 | 16.79 | -11.74 |
| Mar | 29.45 | -24.45 | -12.96 | 95.58 | 17.22 | -28.30 | -27.09 | -44.72 |
| Apr | 51.41 | -53.29 | -53.56 | 48.40 | 67.50 | -4.66 | 21.17 | -62.77 |
| May | -13.47 | -39.58 | 42.09 | 97.79 | 70.22 | -22.72 | -5.76 | -11.06 |
| Jun | 30.95 | -37.45 | -18.38 | -25.96 | -11.88 | 8.19 | -1.25 | 24.42 |
| Jul | 21.07 | 11.60 | -32.84 | 67.62 | 65.03 | -17.85 | 10.92 | 2.60 |
| Aug | 5.05 | -19.56 | -8.62 | -1.57 | 13.13 | 2.21 | -39.67 | -13.87 |
| Sep | -19.58 | -11.01 | -11.77 | -49.95 | 96.22 | -34.25 | -6.50 | 48.99 |
| Oct | -38.50 | -27.36 | -30.10 | 43.63 | 6.83 | -23.09 | 10.06 | 15.51 |
| Nov | -11.90 | 31.00 | -5.43 | 15.68 | 96.02 | -19.52 | 23.71 | -21.95 |
| Dec | -10.99 | 39.12 | -14.88 | -20.92 | 38.12 | 2.61 | 28.30 | -35.42 |
| Year | 3.66 | -10.84 | -14.99 | 27.62 | 42.68 | -6.29 | -0.69 | -21.13 |

## Table 20. Stress Period Departures from Mean *R* from GIS Model

| Month | Departure from Monthly Mean Recharge, *R*, in % | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Period 1 '42-'51 | Period 2 '52-'56 | Period 3 '57-8/61 | Period 4 9/61-'64 | Period 5 '65-'69 | Period 6 '70-'83 | Period 7 '84-'90 | Period 8 '91-'94 |
| Jan | 20.46 | -17.90 | 4.28 | 112.92 | 42.34 | 38.65 | -50.71 | -58.21 |
| Feb | -9.23 | -19.95 | -57.88 | -74.44 | 35.10 | 14.47 | 25.98 | -17.25 |
| Mar | 52.34 | -40.90 | -22.40 | 178.84 | 30.20 | -46.39 | -44.67 | -69.27 |
| Apr | 100.92 | -76.76 | -77.04 | 94.66 | 135.11 | -8.18 | 39.93 | -91.73 |
| May | -27.12 | -60.09 | 105.47 | 280.84 | 191.78 | -41.50 | -12.35 | -24.11 |
| Jun | 51.13 | -40.38 | 35.09 | -29.06 | -15.09 | 13.40 | -2.08 | 39.81 |
| Jul | 29.69 | 14.53 | -36.48 | 130.86 | 124.92 | -21.00 | 14.74 | 4.14 |
| Aug | 7.81 | -25.52 | -12.85 | -2.43 | 20.14 | 3.47 | -44.44 | -18.92 |
| Sep | -32.73 | -19.04 | -20.30 | -67.92 | 269.25 | -49.01 | -11.65 | 112.55 |
| Oct | -64.72 | -51.25 | -54.60 | 100.38 | 16.27 | -46.16 | 21.00 | 34.75 |
| Nov | -19.19 | 53.83 | -9.33 | 26.68 | 179.62 | -31.24 | 40.79 | -34.38 |
| Dec | -15.08 | 54.91 | -20.26 | -27.75 | 54.20 | 3.20 | 39.41 | -44.62 |
| Year | 10.91 | -9.71 | -20.41 | 63.41 | 73.452 | -2.71 | -0.85 | -41.06 |

## Table 21. Stress Period Pumpage Input

| Well | Average Pumpage mgd[a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Period 1 '42-'52 | Period 2 '52-'56 | Period 3 '57-'8/61 | Period 4 '9/61-'64 | Period 5 '65-'69 | Period 6 '70-'83 | Period 7 '84-'90 | Peric '91- |
| [b]Upper Tunnel | 0.223 | 0.103 | 0.040 | 0.027 | 0.042 | 0.026 | 0.051 | |
| [b]Lower Tunnel | 0.206 | 0.112 | 0.115 | 0.138 | 0.198 | 0.094 | 0.107 | 0 |
| Shaft 2 | 0.216 | 0.140 | 0.157 | 0.109 | 0.058 | 0.060 | 0.435 | 0 |
| Shaft 3 BH | 0 | 0 | 0.596 | 0.378 | 0.291 | 0.409 | 0.310 | |
| Well 1 | 0.029 | 0.038 | 0.095 | 0.073 | 0.002 | 0.119 | 0.286 | 0 |
| Well 2 | 0.171 | 0.360 | 1.008 | 0.287 | 0.360 | 0.374 | 0.355 | 0 |
| Well 3 | 0.005 | 0.196 | 0.194 | 0.125 | 0.058 | 0.319 | 0.345 | 0 |
| Well 4 | 0.003 | 0.105 | 0.219 | 0.160 | 0.023 | 0.315 | 0.766 | 0 |
| Well 5 | 0.016 | 0.232 | 0.099 | 0.066 | 0.077 | 0.234 | 0.288 | 0 |
| Well 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0.019 | 0 |
| Well 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 0.868 | 1.287 | 2.516 | 1.364 | 1.110 | 1.949 | 2.961 | 2 |
| Well | Average Pumpage cfd[c] (for MODFLOW input) | | | | | | | |
| [b]Upper Tunnel | 29808.2 | 13775.2 | 5300.6 | 3605.6 | 5581.9 | 2420.3 | 6850.1 | |
| [b]Lower Tunnel | 27520.9 | 15015.9 | 15355.8 | 18411.2 | 26490.8 | 12573.6 | 14238.1 | 76 |
| Shaft 2 | 28880.0 | 18701.5 | 21029.9 | 14583.7 | 7742.2 | 8063.5 | 58159.0 | 685 |
| Shaft 3 BH | 0 | 0 | 79698.8 | 50545.4 | 38849.3 | 54657.8 | 51392.2 | |
| Well 1 | 3874.6 | 5087.2 | 12737.3 | 9812.9 | 315.7 | 15842.0 | 39261.1 | 147 |
| Well 2 | 222856.5 | 48125.5 | 133743.4 | 38413.4 | 48189.4 | 49993.1 | 47487.9 | 258 |
| Well 3 | 623.3 | 26223.3 | 25973.4 | 16742.8 | 7784.5 | 42678.7 | 46053.6 | 380 |
| Well 4 | 340.0 | 14062.8 | 29297.0 | 21412.2 | 3128.8 | 42078.8 | 102414.9 | 67 |
| Well 5 | 2174.4 | 31078.2 | 13239.3 | 8858.4 | 10254.2 | 31291.9 | 38439.5 | 14 |
| Well 6 | 0 | 0 | 0 | 0 | 0 | 0 | 2519.4 | 44 |
| Well 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 19 |
| Total | $1.16x10^5$ | $1.72x10^5$ | $3.36x10^5$ | $1.82x10^5$ | $1.48x10^5$ | $2.61x10^5$ | $3.96x10^5$ | 3.0 |

a. million gallons per day
b. Gravity flow
c. cubic feet per day

Several important observations resulted from the transient analysis. First, in earlier transient simulations it was found that the transient windward water levels were to low and the leeward were too high. This prompted a change in the internal boundary conditions by adding several additional horizontal flow boundaries in the Puu Kawelo and Puu Mahana area. Additionally, a mauka horizontal flow boundary in the Shaft 3 bulkhead was removed since the tunnel here does extend for some distance. These changes, in turn, necessitated a recalibration effort to meet the initial steady-state conditions which was then followed again by transient analysis. This circular type of calibration effort resulted in a much better match for all observed water levels. Secondly, there is no one best *S* value which can accommodate the entire island on the regional scale. This should cast some doubt on the validity of the initial assumptions of homogeneity and isotropy on the regional scale. From the various figures in Appendix F it can be seen that some simulated transient water levels match observed trends better than others for different *S* values. Table 22 was constructed to show these differences in matching trends.

**Table 22. Best Match for Transient Conditions**

| Source | Storage Coefficient, *S* | | | | |
|---|---|---|---|---|---|
| | 0.01 | 0.05 | 0.1 | 0.2 | 0.4 |
| [a]Upper Tunnel | best | | | | |
| [a]Lower Tunnel | best | | | | |
| Shaft 1 | | | | | best |
| Shaft 2 | | | | | best |
| [b]Shaft 3 BH | | | | best | |
| Well 1 | best | | | | |
| Well 2 | | | | | best |
| Well 3 | | best | | | |
| Well 4 | | | | best | |
| Well 5 | | | best | | |
| Well 6 | | | | | |
| Well 9 | | | | | |
| Total | 3 | 1 | 1 | 2 | 3 |

a. Gravity flow
b. Pumped in model but actually gravity flow tunnel

An additional transient run was made to investigate and provide a estimate of how close the present situation is to steady-state conditions. The long-term average pumpage for each source was induced on the best-fit calibrated model and run for 1000 years into the future. A single *S* value 0.1 was chosen for this exercise. Results for each well in this exercise is found in Appendix G. According to this exercise, water levels in wells are between 10%-90% of steady-state water levels for the long-term pumpage between 1942 to 1994 excluding well 5.

## Model Sensitivity Analysis

As noted earlier, the trial-and-error approach of parameter estimation does not guaran the statistically best fit, and sensitivity analysis is necessary. Sensitivity analysis is sim observing the water level response changing an individual hydraulic parameter on the best fit c ibration while holding all other parameters and boundary location conditions constant. This done to help quantify the uncertainty of the calibrated Lana'i numerical model. Specifically, individual regionally effective model parameters are; the global and caldera horizontal hydrau conductivity, $K_h$, the horizontal-flow barrier (HFB) hydraulic characteristic, $HYDCHR_u$, north and south coastal streambed conductance term, ***SC***, the tunnel drain conductance term ***L*** and the input flux of recharge, ***R***. Each parameter was varied individually by increasing decreasing its calibrated value over the range of ± 100% and the model run to steady-state. T changes in resulting ground-water levels between the simulated steady-state best fit calibrat and sensitivity runs is summarized in Figure 39, pg. 95.

It is important to understand that Figure 39, pg. 95 shows the sensitivity of the calibra model based only on the internal boundary geometry, the simplified assumptions of regio homogeneity and isotropy for the hydraulic values of these boundaries, and the steady-state c ditions discussed earlier. Figure 39, pg. 95, does not include the model's sensitivity to chang mathematical or internal boundary geometry nor initial seed conditions, such as starting head v ues for a specific computer run. Changing internal boundary conditions will create an alternat solution which could be calibrated, graphed similarly, and would also show a trend towards a z (0) mean absolute error along the x-axis of the figure. What is also missing from Figure 39 is models's sensitivity to changes in internal boundary conditions. Through the calibration effo was clear that the Lana'i model is also quite sensitive to small changes in the locations of inter boundary conditions. For example, removing only a few horizontal flow boundaries had dram regional and local effects on water levels. In fact, other recent studies (Meyer, & others, 19 have shown that water level responses to pumping in compartmentalized high-level type aqui are very sensitive in numeric models. Changing the calibrated boundary geometry, in effect, c ates a new model.

From the sensitivity analysis it is clear that the model is most sensitive to changes in horizontal flow boundary, $HYDCHR_u$ and recharge, ***R***. The sensitivity to $HYDCHR_u$ an should not be surprising since these internal boundaries are known to be a reason for high-le aquifers and their observed sensitivity to climactic conditions in the real world. Since the mc is sensitive to $HYDCHR_u$ it follows that the model must then be sensitive to the locations of th internal boundaries. This supports the statement made in the preceding paragraph that the mc is very sensitive to changes in boundary locations but is difficult to show in the graphical mar as done in Figure 39, pg. 95.

A few other statements can be made from the behavior of the sensitivity curves. model seems to be equally sensitive to equal changes in both $HYDCHR_u$ and ***R***. This indic that the two are correlated which makes sense since the lack of either one would result in no h level water. Changes to other parameters in the model do not induce significant changes u much larger percentage increases than $HYDCHR_u$ and ***R***, and even then the MAE is much les

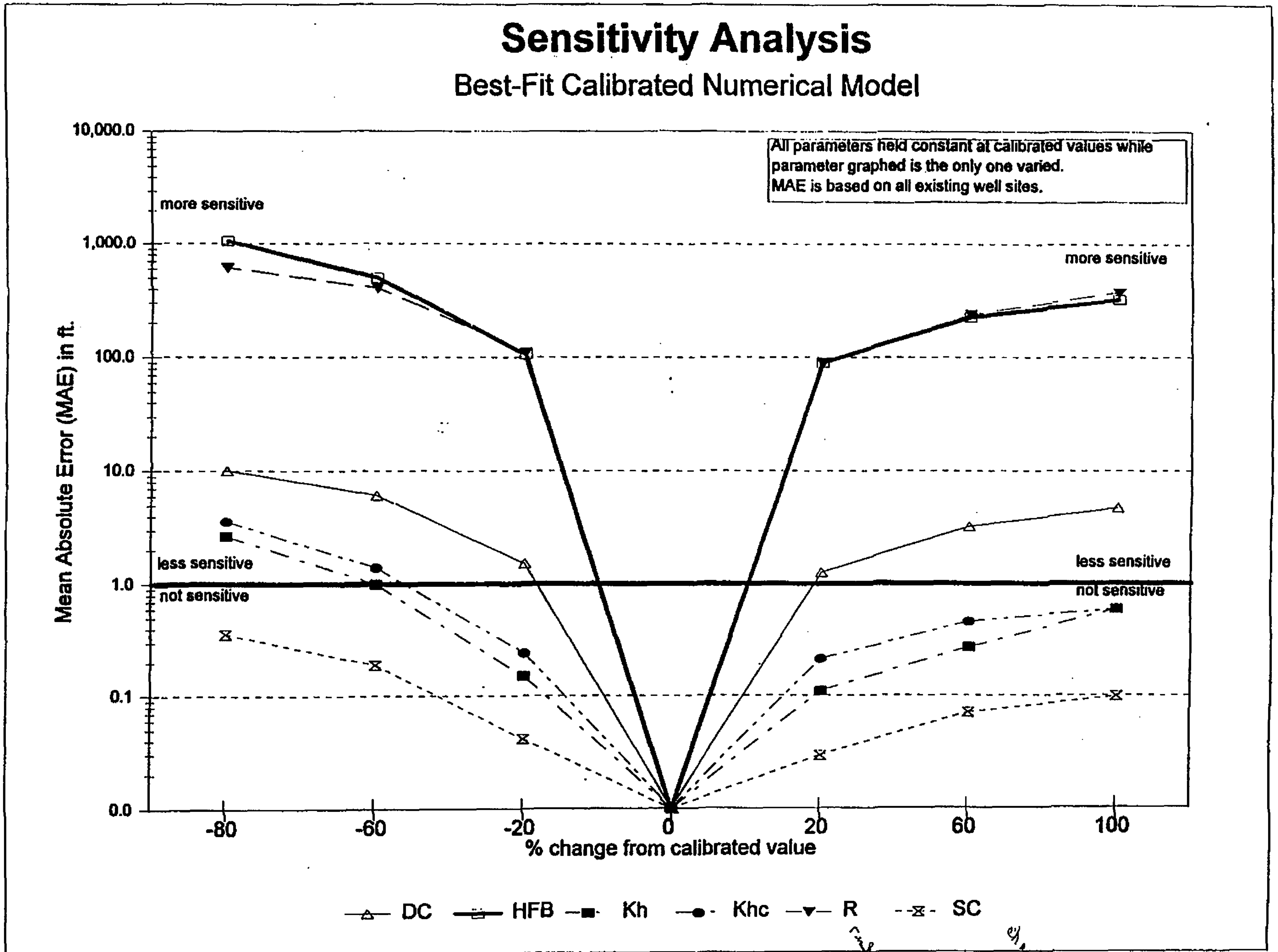



Figure 39. Sensitivity Curves of Calibrated Model

## Model Predictive Runs

Using the best-fit calibrated model as the base, six (6) predictive scenarios were inve gated to assess potential regional ground-water level responses to various stresses. The first p dictive run was made to assess the impacts of pumping at the long-term '42-'94 avera Secondly, fog-drip only is removed (i.e. no pumpage). Third, the model is pumped at the curr CWRM estimate of island-wide sustainable yield (6 mgd) through existing wells normally op ated. The fourth predictive run combines the impacts of scenarios 2 and 3; removing fog-drip imposing 6 mgd pumpage. Fifth, the Wells 1 & 9 in the caldera were pumped alone with all ot wells turned off. Lastly, a potential pumpage distribution specified by LCo. is investigated.

Pumpage was not constrained by the actual physical limitations of each well. Estima future withdrawals from existing wells to meet the 6 mgd pumpage for scenarios 3 & 4 are sim a matter of convenience. This approach is probably not an accurate prediction of actual fut operations but it serves as an objective way of distributing 6 mgd pumpage. Not knowing future distribution of such an increase in pumpage, additional necessary pumpage was distribu evenly amongst the existing recent annual average pumpage for each high-level pumped w Future pumpage for Scenario 5, concerning the caldera, is evenly distributed between Wells 1 9. Pumpage in scenario 6 was specified by LCo.'s hydrologic/engineering consultant. The pun age values used in these predictive scenarios are summarized in Table 23.

**Table 23. Individual Well Pumpage for Predictive Model Runs**

| Wells | SCENARIO WELL PUMPAGES | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 & 4 | | 5 | | 6 | |
| | '42-'94 Average | | No Fog | | Current CWRM SY | | Caldera Only | | Lanai Co | |
| | mgd | cfd | mgd | cfd | mgd | cfd | mgd | cfd | mgd | c |
| Upper Tunnel | [a]ff | ff | ff | ff | ff | ff | ff | ff | ff | |
| Lower Tunnel | ff | ff | ff | ff | ff | ff | ff | ff | ff | |
| Shaft 2 | 0.196 | 26,190 | 0 | 0 | 1.044 | 139,618 | 0 | 0 | 0.500 | 66 |
| Well 1 | 0.116 | 15,479 | 0 | 0 | 0.690 | 92,229 | 0.325 | 43,450 | 0.270 | 36 |
| Well 2/Shaft 3 | 0.721 | 83,021 | 0 | 0 | 0.604 | 80,786 | 0 | 0 | 0.300 | 40 |
| Well 3 | 0.205 | 27,398 | 0 | 0 | 0.683 | 91,291 | 0 | 0 | 0.300 | 40 |
| Well 4 | 0.273 | 36,483 | 0 | 0 | 0.918 | 122,668 | 0 | 0 | 0.400 | 53 |
| Well 5 | 0.155 | 20,738 | 0 | 0 | 0.531 | 71,010 | 0 | 0 | 0.400 | 53 |
| Well 6 | 0.029 | 3,919 | 0 | 0 | 0.746 | 99,744 | 0 | 0 | 0.300 | 40 |
| Well 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.200 | 2 |
| Well 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.300 | 4 |
| Well 9 | 0.012 | 1,571 | 0 | 0 | 0.784 | 104,733 | 0.325 | 43,450 | 0.270 | 3 |
| Well 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.280 | 3 |
| [b]Total | 1.607 | 214,800 | 0 | 0 | 6.000 | 802,079 | 0.650 | 86,900 | 3.520 | 47 |

a. ff - free-flowing, no induced pumping.
b. Ignores any contribution of tunnel flow to total ground water removal via artificial means.

# Predictive Run Results

Before discussing predictive run results, it is an appropriate time to clarify the issue of sustainable yield and regional water-level response. The reader may recall from Table 1, pg. 3, the issue regarding the definition of the term 'safe yield' between Stearns and Anderson. The issue is significant since it highlights what other respected hydrologists (Theis, 1994 & Lohman, 1979) have identified as the "Alice-in-Wonderland" syndrome where there is a plethora of definitions for aquifers and safe yields which complicate the communication and representation of these hydrologic concepts. Likewise, the definition of sustainable yield has many different meanings to many different people both familiar and unfamiliar to ground-water hydrology. Therefore, it is important to understand that the results from the six (6) predictive runs do not in any way define the sustainable yield for Lana'i. Instead, the numerical model will only attempt to predict Lanai's *regional* or *aquifer* ground-water level response to these particular stress scenarios.

This leads one to another issue which must be clarified before interpreting predictive results. It is important to understand that *regional* or *aquifer* responses predicted by the model **do not** predict *localized* or *discrete* water levels over areas smaller than a single cell grid. *Local* changes in ground-water levels for locations within grid cells, such as pumping wells, are only predicted insofar that they reside in a particular grid cell whose water level is the *average* water level over a 2000' by 2000' area. In simply terms, the numerical model is predicting the average regional water level at each cell node which represents a 2000 ft. by 2000 ft. area and not a typical 12 to 18-inch diameter well. One would have to increase the discretization of the model grid, i.e. increase the number cells by reducing cell sizes to the diameter of a typical well (around 2' x 2') to have the numerical model address such a localized question. Not only would such a change dramatically increase the amount of work and time in constructing a new model grid and boundaries but heterogeneities and anisotropies would play a more significant role at smaller scales and increase the difficulty in calibration. If and once this is achieved then an additional difficulty would need to be addressed. Localized changes in ground-water levels in pumping cells are further complicated by well efficiencies which can increase actual drawdown beyond theoretical aquifer or regional drawdowns. MODFLOW does not account for such well efficiencies and assumes that wells are 100% efficient. Therefore, one would have to additionally estimate well efficiencies which depend on many factors that have been described earlier in this report. Efficiencies of 70% to 80% are usually obtainable if a well is properly designed, constructed, and developed (Driscoll, 1986) but may be as poor as 50%, where actual pumping well drawdowns would double, or worse. In all, such localized ground water level detail is beyond the scope of this report.

The results of the six (6) scenarios according to Table 23, pg. 96, are summarized graphically in Figures 40 through 53 on the following pages. One general statement which can be made is that except for Scenario 1, in all scenarios the Maunalei tunnel sources will eventually dry up at steady-state conditions. Other statements are now broken down by scenario.

## Scenario 1: '42-'94 Average Pumpage

This scenario, steady-state ground-water levels response to the long-term average pumi age has actually already been covered in the determination of the "best-fit" calibration (see Figu: 38, pg. 89). In the plan view, there does not appear to be much difference between the "best-fi water level contours (Figure 33, pg. 72) with the water level contour map for this scenario, Figu: 40, pg. 99, except that the areal extent of some higher-level contours are a bit smaller. Drawdov contours shown in Figure 41, pg. 100, show that the regional water levels should decrea: between 50 to 250 ft. with the greatest drawdown near Shaft3/Well 2 and Well 4. The Low Maunalei Tunnel should have a steady-state flow around 183,000 gpd while the Upper Maunal Tunnel should dry up if the long-term average pumpage is continued or exceeded and long-ter recharge is unchanged. Observed static water levels and recently reported tunnel flows a regionally consistent with this prediction with the understanding that steady-state has not yet be achieved.

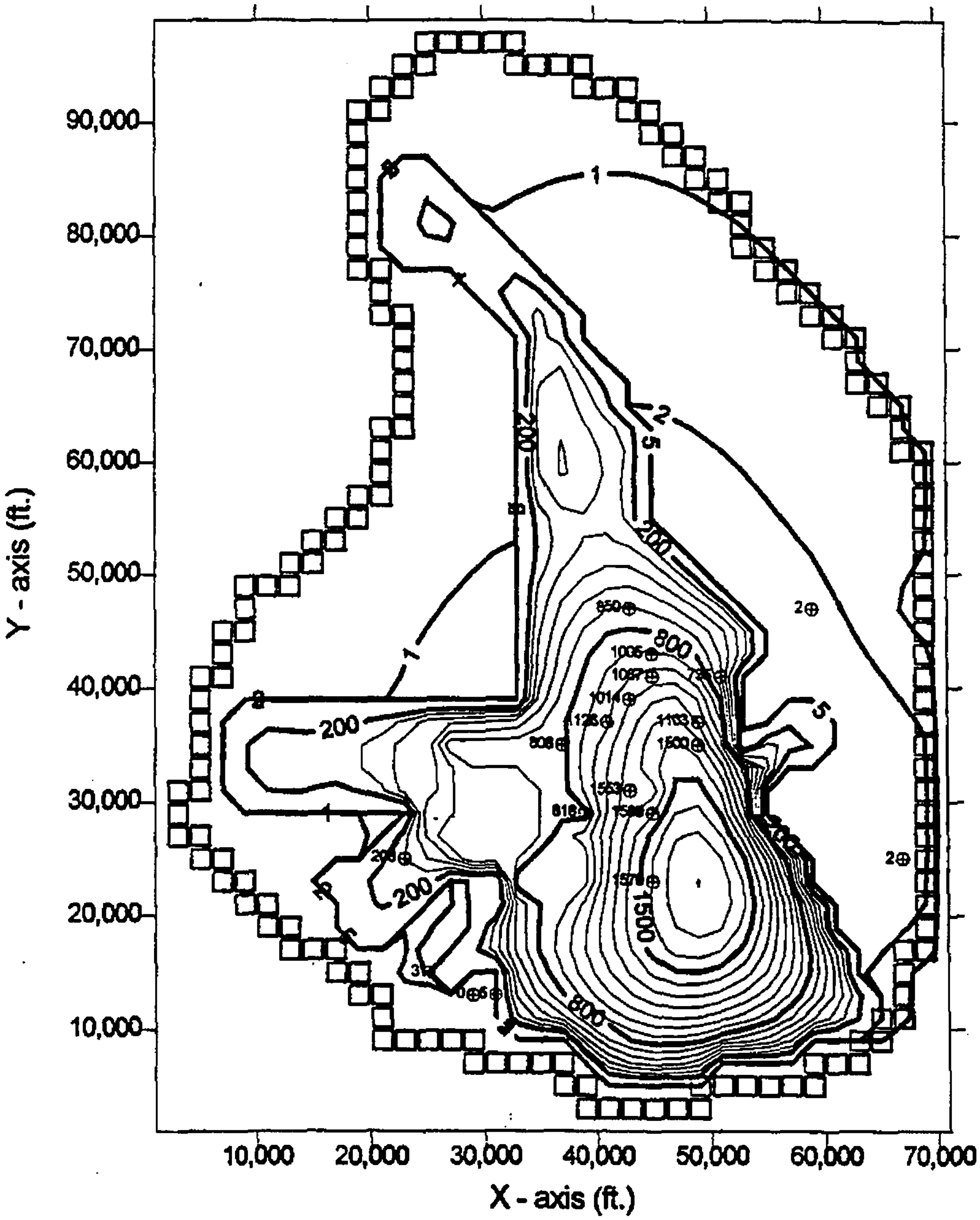
Maximum steady-state regional drawdown predicted by the model is 264 feet. Wells 4 5 in recent times have approached this drawdown on particular months and have actual exceeded it during pumping (see Figures 17& 20). Otherwise, no reported static or pumpi drawdown has exceeded this value.

The predicted time necessary to reach steady-state is on the order of 200 to several hu dred years. Figure 42, pg. 101, compares observed water levels with simulated water levels tak out 1000 years from 1942. This transient figure for other wells is found in Appendix G. Like t other transient runs done during calibration on only the past 50 years, found in Appendix F, the does not appear to be one universal storage coefficient value for all wells. From Figure 42, it c be seen that through various storage coefficients the time needed to reach steady-state is on t order of 200 to several hundred years.

Comparing model predicted regional drawdowns with observed static drawdowns in we it can be generally said that the range of actual aquifer drawdowns due to long term pumping somewhere between 20% to 95% of steady-state drawdowns. This statement is independent the time necessary to reach steady-state conditions but is only a comparison of steady-state dra downs predicted. This statement does not apply to Wells 6 & 9 which are relatively new and ha very little data compared to other older sources on the island and Well 1 whose recent pumpage much greater than the historical long-term pumpage averaged over 52 years.

## Simulated Regional Steady-State Ground Water Level Contours for Lanai

**Best-Fit Calibration with Existing Wells Pumped to '42-'94 Ave mgd**




MODFLOW INPUT DATA

Storage Coeffcient. = 0 (i.e. non-transient)
Global Kh = 1000 ft/d
Caldera Kh = 100 ft/d
River conductance Klw/m
with lw=4,000,000 sq.ft.,m=100 ft.,@z=0 ft. msl
where South K=1000 ft/day = 400,000,000 sq.ft./day
where North K= 0.1 ft/day = 40,000 sq.ft./day
Horizontal flow boundaries = 895
Horizontal flow boundary conductance K/w = 0.0000501/day
Bottom elevation = -400 ft.
Area of recharge = 140.83 sq. mi.
Recharge = 61.60 mgd
Pumping = 1.790 mgd
Flow from Lower Maunalei Tunnel = 0.183 mgd
Flow from Upper Maunalei Tunnel = 0.000 mgd

MODFLOW OUPUT THROUGH SURFER GRAPHICS

Maximum water level = 1803 ft. above mean sea level.
(contour truncated at 1800 ft. above msl)

⊕ - Well locations with original water levels.

☐ - Numerical coastline of Lanai

CLOSURE CRITERIA

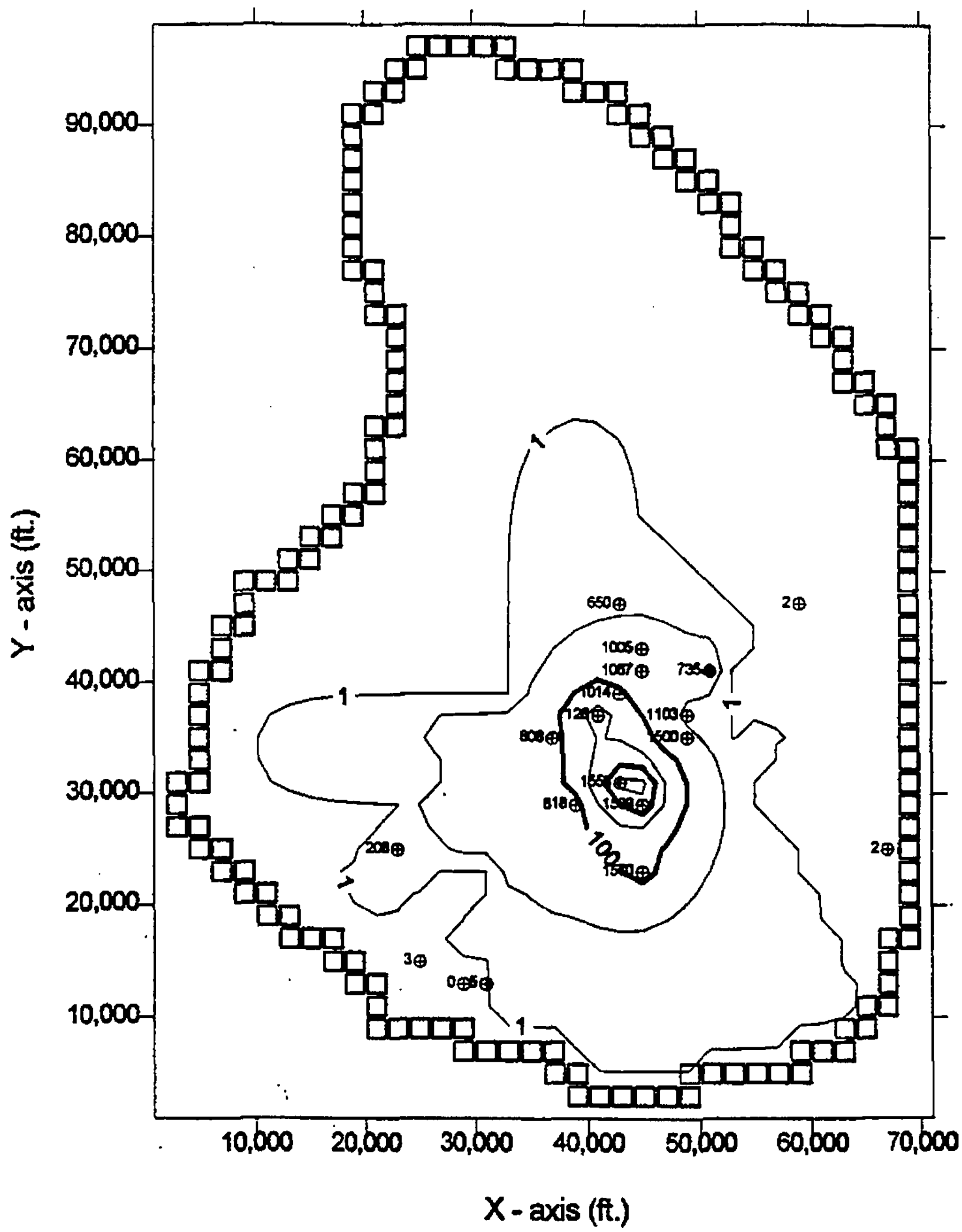
Maximum water level change < 0.001
Water balance < 1% (Actual = -0.05%)



Figure 40. Scenario 1 Predictive Regional Ground-Water Level Contours

# Simulated Regional Steady-State Drawdown Contours for Lanai

**Best-Fit Calibration with Existing Wells Pumped to '42-'94 Ave mgd**




MODFLOW INPUT DATA

Storage Coefficient. = 0 (i.e. non-transient)
Global Kh = 1000 ft/d
Caldera Kh = 100 ft/d
River conductance K:w/m
with lw=4,000,000 sq.ft.,m=100 ft.,@ z=0 ft. msl
where South K=1000 ft/day = 400,000,000 sq.ft./day
where North K= 0.1 ft/day = 40,000 sq.ft./day
Horizontal flow boundaries = 895
Horizontal flow boundary conductance K/w = 0.0000501/day
Bottom elevation = -400 ft.
Area of recharge = 140.83 sq. mi.
Recharge = 61.60 mgd
Pumping = 1.790 mgd
Flow from Lower Maunalei Tunnel = 0.183 mgd
Flow from Upper Maunalei Tunnel = 0.000 mgd

MODFLOW OUPUT THROUGH SURFER GRAPHI(

Maximum drawdown = 264 ft.
(contour truncated at 200 ft.)

⊕ - Well locations with original water levels.

☐ - Numerical coastline of Lanai

CLOSURE CRITERIA

Maximum water level change < 0.001
Water balance < 1% (Actual = -0.05%)

Figure 41. Scenario 1 Predictive Regional Drawdown Contours

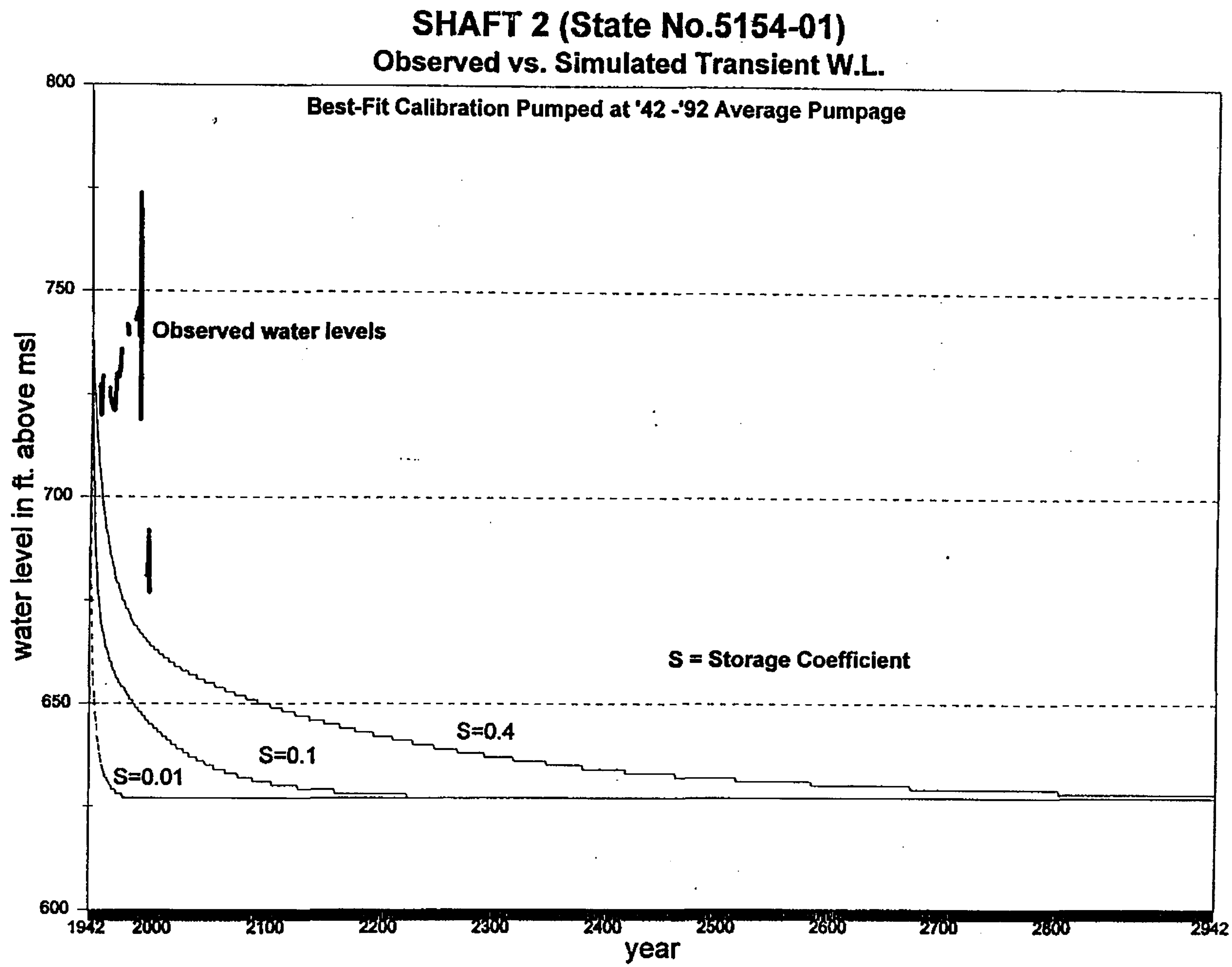



Figure 42. Observed vs. Simulated Transient Water Levels for Shaft 2

## Scenario 2: Total Fog Drip (*FD*) Removal

If ***FD*** is completely removed from the "best-fit" calibrated model, regional water leve around existing high-level wells are predicted to drop between 100 to 700 ft. (see Figure 44, p 104) and impact a much broader area (see Figure 43, pg. 103) than the existing long-term pum age. This greater impact is expected since ***FD*** is estimated at about 8.9 mgd whereas long-ter pumpage is around 1.8 mgd. The major impacts are confined within the center most portion of tl high-level aquifer (see Figure 50, pg. 112) while the outer fringes of the high-level aquifer are n as affected. This is expected since this is the area above the 2000' elevation where rainfall preci itation is augmented.

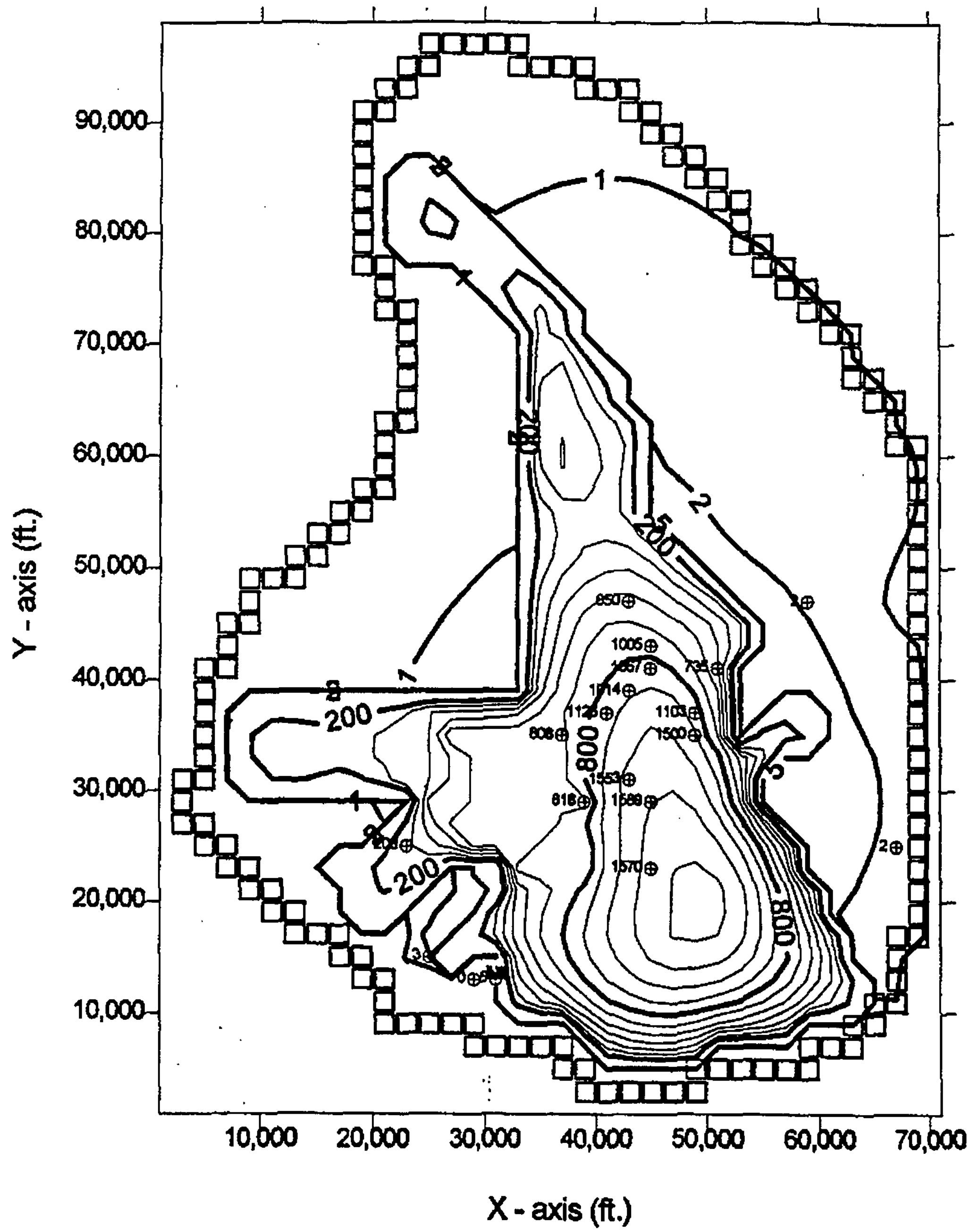
Transient analysis of this scenario, as shown in Figure 45, pg. 105, assumes $S = 0.1$ ai indicates that it would take between 400 to 600 years to achieve complete steady-state. Howeve much of the changes should be seen in the first 100 years of such a drastic change. These tv observations indicate that if a significant amount of ***FD*** were reduced in the past 50 years th some of the drawdown seen in the wells may be due to a reduction in ***FD***, but it will also take long time before the full effects of such a reduction are complete.

The insight provided by this predictive run shows that ***FD***, or some other form of precip tation which augments rainfall, is an important contributor to the ground water supply on Lana This should not be surprising given the sensitivity of the calibrated model to recharge. Water le els can therefore be greatly affected by this one recharge component alone. In fact, Bowl (1974) had attributed some of the decline in ground water levels due to the reduction of fore cover on the island which would have an effect on ***FD*** although other factors such as changes runoff may be involved. Since ***FD*** is dependant on forest cover this scenario makes a particula strong case for protecting forest cover, particularly in the regions above the 2000' elevation co tour where ***FD*** is more prevalent.

What is most interesting about this particular scenario is that it can be viewed as a pote tial optimized well configuration scenario. Assuming long-term recharge, including ***FD***, conti ues, then placing wells at every cell node (i.e. every 2000 ft.) in the region above the 200 elevation and pumping at a rate which matches the effect of ***FD*** removal at that cell node wou result in the same aquifer response as removing ***FD*** only. Thus, such an optimized well config ration could pump 8.9 mgd with similar regional effects as shown in Figures 43 to 45. This do not mean to say that such a well configuration, which itself is questionable considering econo ics, power, and other physical constraints, would result in fully operational pumpage sche since localized water levels depend on other criteria such as well efficiencies or water quali However, the model suggests that from the aquifer's point of view such an optimized scheme possible.

## Simulated Regional Steady-State Ground Water Level Contours for Lanai

**Best-Fit Calibration minus Fog-Drip Only**




MODFLOW INPUT DATA

Storage Coeffcient. = 0 (i.e. non-transient)
Global Kh = 1000 ft/d
Caldera Kh = 100 ft/d
River conductance Klw/m
with lw=4,000,000 sq.ft.,m=100 ft.,@ z=0 ft. msl
where South K=1000 ft/day = 400,000,000 sq.ft./day
where North K= 0.1 ft/day = 40,000 sq.ft./day
Horizontal flow boundaries = 895
Horizontal flow boundary conductance K/w = 0.0000501/day
Bottom elevation = -400 ft.
Area of recharge = 140.83 sq. mi.
Recharge = 53.10 mgd
Pumping = 0 mgd
Flow from Lower Maunalei Tunnel = 0.000 mgd
Flow from Upper Maunalei Tunnel = 0.000 mgd

MODFLOW OUPUT THROUGH SURFER GRAPHICS

Maximum water level = 1230 ft. above mean sea level.
(contour truncated at 1200 ft. above msl)

⊕ - Well locations with original water levels.

□ - Numerical coastline of Lanai

CLOSURE CRITERIA

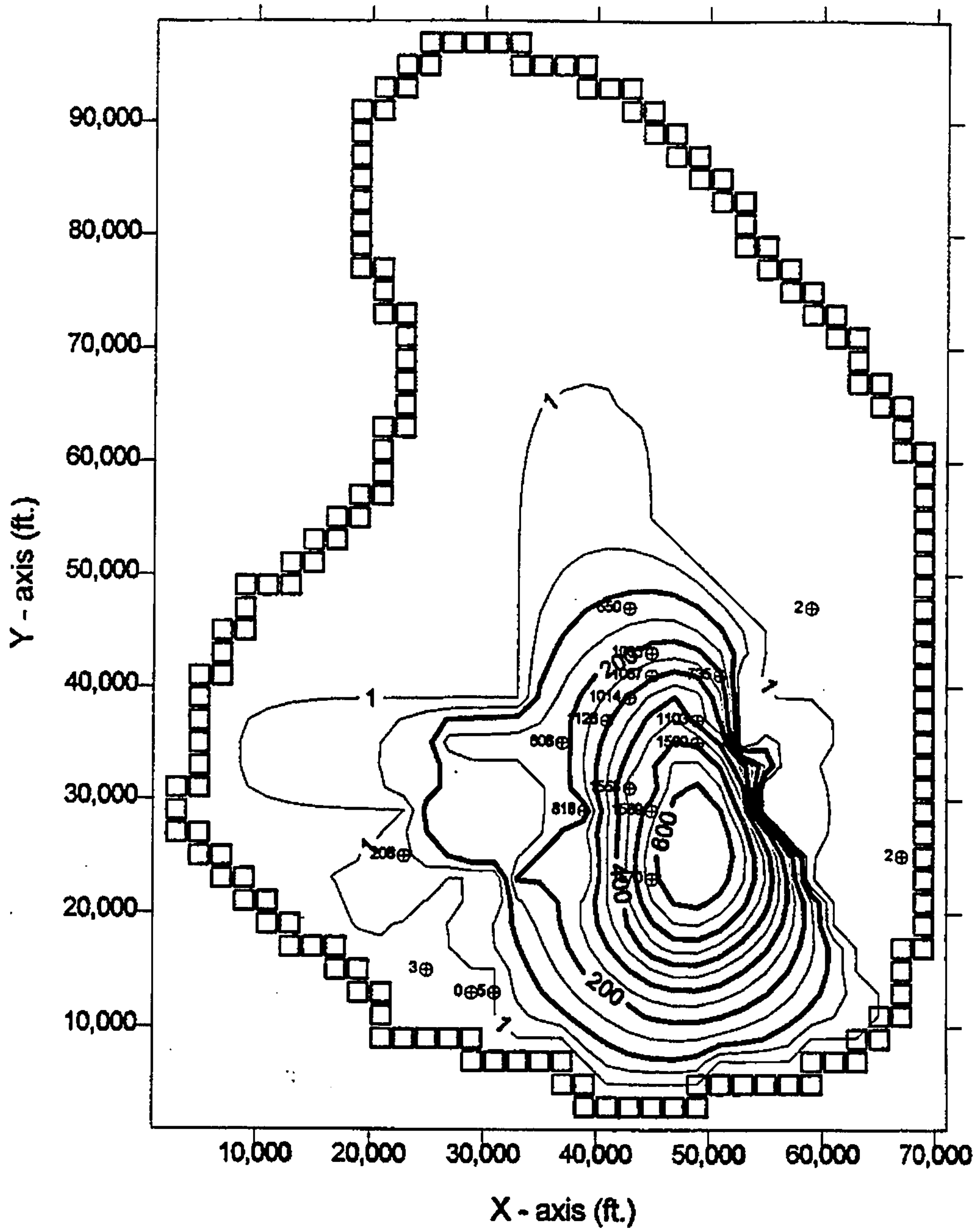
Maximum water level change < 0.001
Water balance < 1% (Actual = -0.05%)



Figure 43. Scenario 2 Predictive Regional Ground-Water Level Contours

## Simulated Regional Steady-State Drawdown Contours for Lanai

**Best-Fit Minus Fog-Drip Only**




MODFLOW INPUT DATA

Storage Coeffcient. = 0 (i.e. non-transient)
Global Kh = 1000 ft/d
Caldera Kh = 100 ft/d
River conductance Klw/m
with lw=4,000,000 sq.ft.,m=100 ft.,@ z=0 ft. msl
where South K=1000 ft/day = 400,000,000 sq.ft./day
where North K= 0.1 ft/day = 40,000 sq.ft./day
Horizontal flow boundaries = 895
Horizontal flow boundary conductance K/w = 0.0000501/day
Bottom elevation = -400 ft.
Area of recharge = 140.83 sq. mi.
Recharge = 53.10 mgd
Pumping = 0 mgd
Flow from Lower Maunalei Tunnel = 0.000 mgd
Flow from Upper Maunalei Tunnel = 0.000 mgd

MODFLOW OUPUT THROUGH SURFER GRAPHIC

Maximum drawdown = 679 ft.
(contour truncated at 600 ft.)

⊕ - Well locations with original water levels.

☐ - Numerical coastline of Lanai

CLOSURE CRITERIA

Maximum water level change < 0.001
Water balance < 1% (Actual = -0.05%)

Figure 44. Scenario 2 Predictive Regional Drawdown Contours

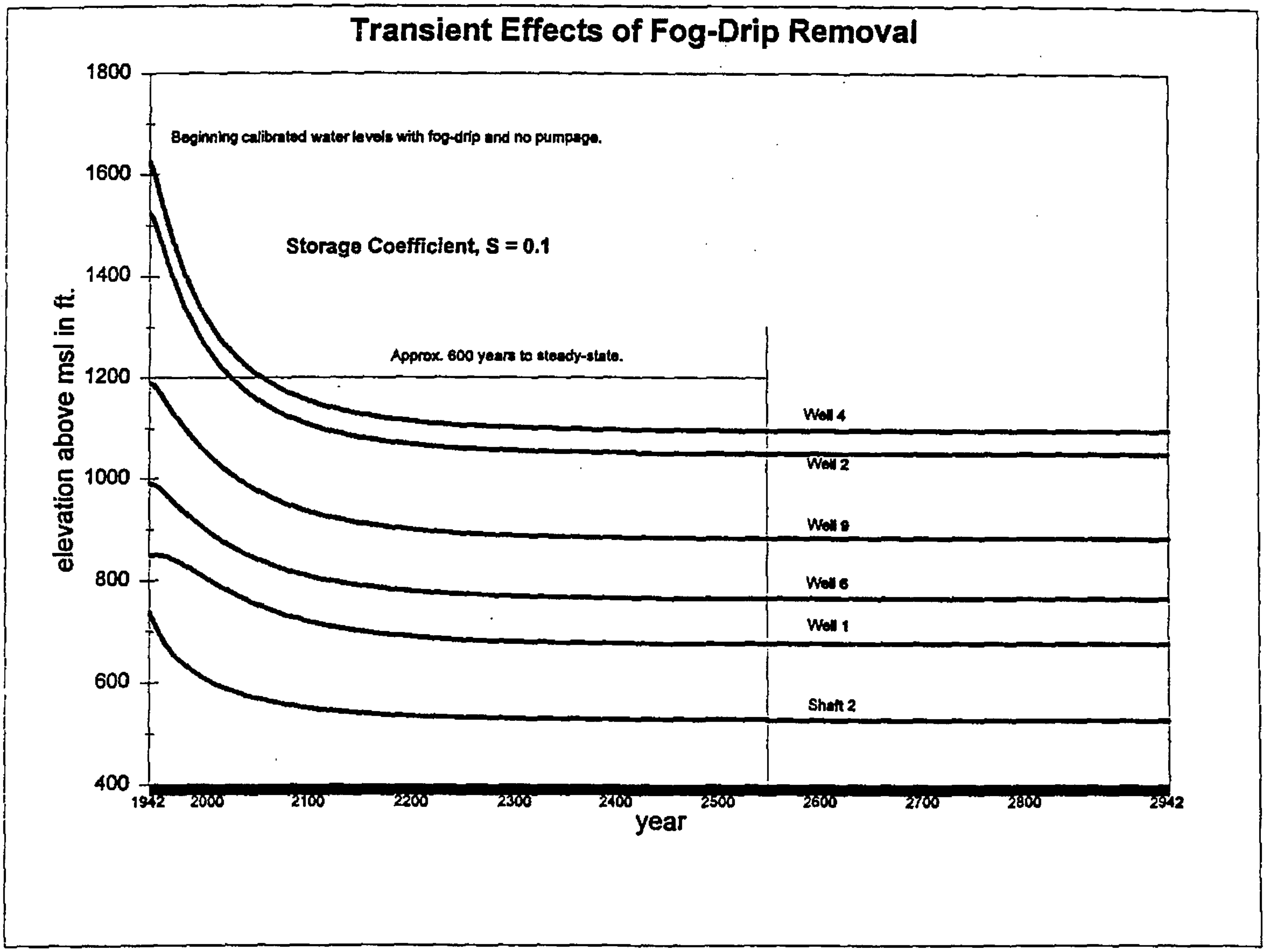



Figure 45. Scenario 2 Transient Time Response to Fog-Drip Removal

## Scenario 3: 6 mgd Pumping From Selected Existing Wells

This predictive scenario has its origin in the current CWRM estimate for sustainable yiel for the Lana'i. Pumpages for this scenario are defined in Table 23, pg. 96.

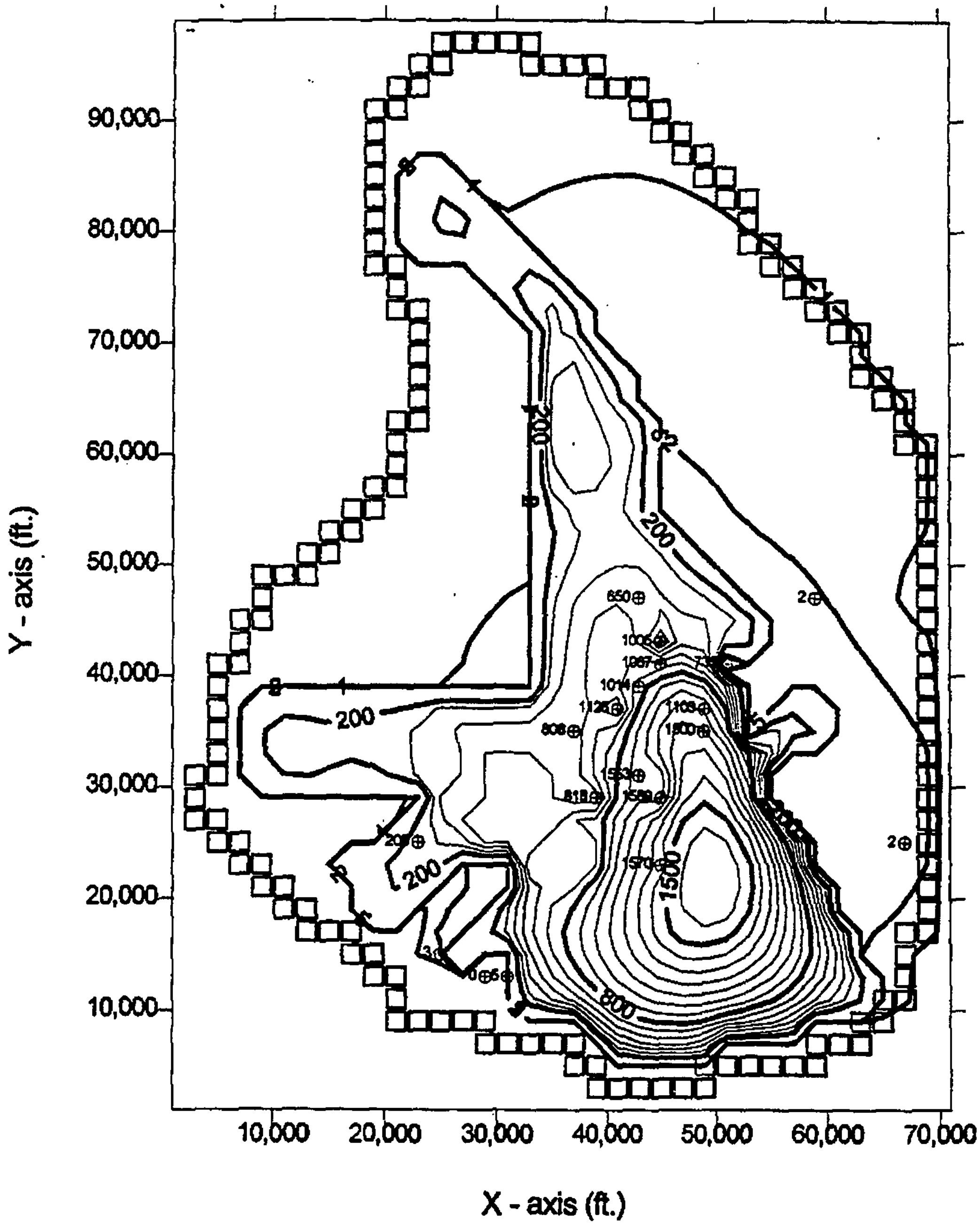
On the regional scale, pumping selected existing wells to 6 mgd results in regional draw downs between 50 to 950 feet over a larger area than the long-term pumpage effects but a smalle area than what the model predicts for Scenario 2; total ***FD*** removal. Figures 46 & 47 show th clearly when one compares these with the corresponding Scenario 2 figures. This is expecte since drawdowns due to 6 mgd pumping through a limited number of wells, rather than spreadin a greater flux removal, total ***FD***, over a larger area, should be more concentrated.

In broad areas around the existing wells regional water levels would decrease on the ord to 300 to 500 feet with the maximum drawdowns occurring at Shaft 2. In fact, the model predic that aquifer water levels at Shaft 2 would go below sea level which would probably render th source unusable. This was the same well problem encountered before GIS recharge was incorpo rated into the model. The historical behavior of this source does not indicate such a drastic eve would result and probably indicates that there are some unresolved local effects associated wi this source.

Although regional water levels remain high at steady-state for this scenario it does n mean the 6 mgd can be achieved under the current well configuration. Again, localized effec will increase drawdowns at the specific well sites and would necessitate the deepening of all exis ing wells which do not reach sea level. Even such a modification may not be enough to develop mgd from the aquifer and additional wells would probably be required.

## Simulated Regional Steady-State Ground Water Level Contours for Lanai

### Best-Fit Calibration with Existing Wells Pumped to 6 mgd




MODFLOW INPUT DATA

Storage Coefficient. = 0 (i.e. non-transient)
Global Kh = 1000 ft/d
Caldera Kh = 100 ft/d
River conductance Kl/w/m
with lw=4,000,000 sq.ft.,m=100 ft.,@ z=0 ft. msl
where South K=1000 ft/day = 400,000,000 sq.ft./day
where North K= 0.1 ft/day = 40,000 sq.ft./day
Horizontal flow boundaries = 895
Horizontal flow boundary conductance K/w = 0.0000501/day
Bottom elevation = -400 ft.
Area of recharge = 140.83 sq. mi.
Recharge = 61.60 mgd
Pumping = 6 mgd
Flow from Lower Maunalei Tunnel = 0.000 mgd
Flow from Upper Maunalei Tunnel = 0.000 mgd

MODFLOW OUPUT THROUGH SURFER GRAPHICS

Maximum water level = 1689 ft. above mean sea level.
(contour truncated at 1600 ft. above msl)

⊕ - Well locations with original water levels.

□ - Numerical coastline of Lanai

CLOSURE CRITERIA

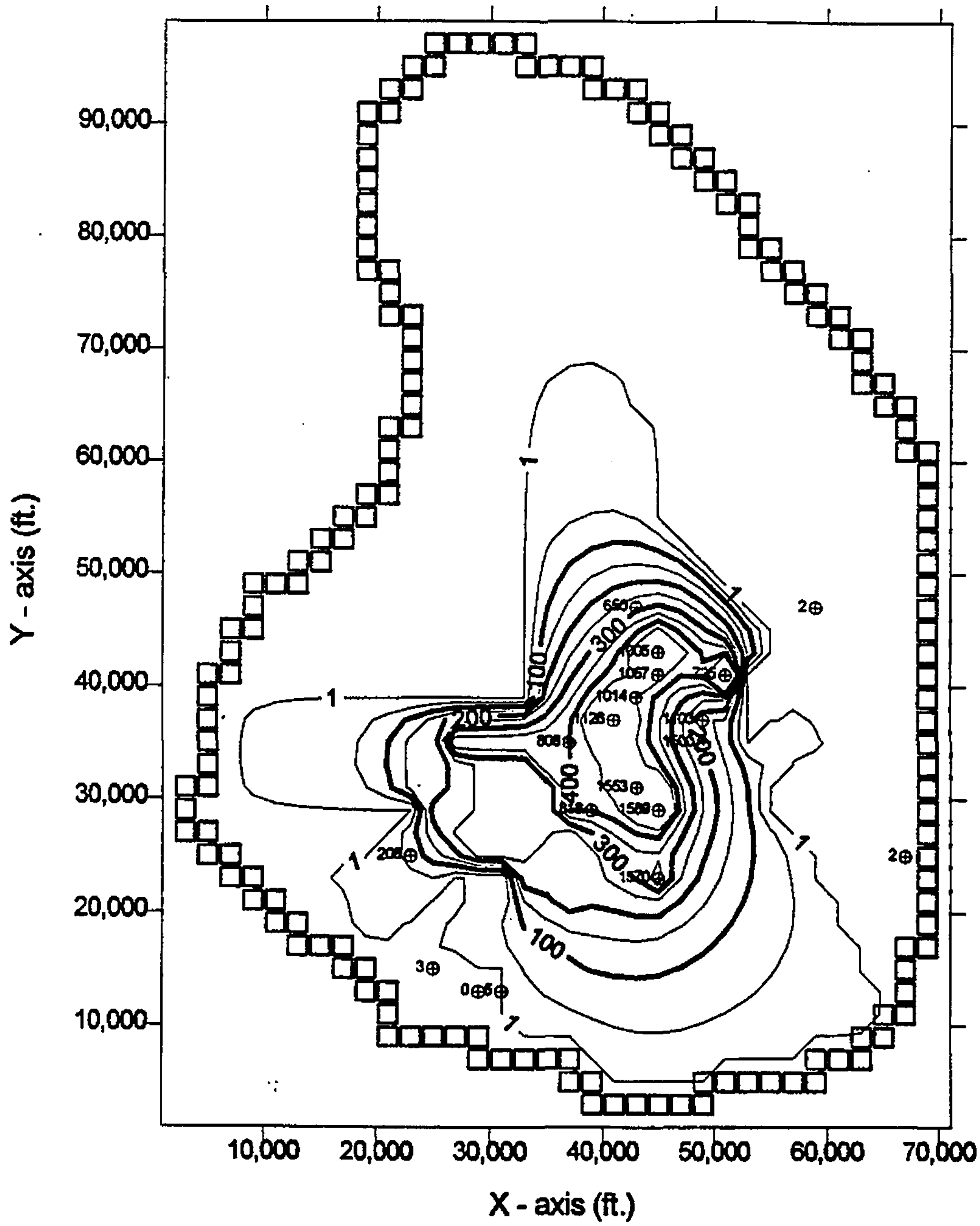
Maximum water level change < 0.001
Water balance < 1% (Actual = -0.05%)



Figure 46. Scenario 3 Predictive Regional Ground-Water Level Contours

## Simulated Regional Steady-State Drawdown Contours for Lanai

**Best-Fit Calibration with Existing Wells Pumped to 6 mgd**




MODFLOW INPUT DATA

Storage Coeffcient. = 0 (i.e. non-transient)
Global Kh = 1000 ft/d
Caldera Kh = 100 ft/d
River conductance Klw/m
with lw=4,000,000 sq.ft.,m=100 ft.,@ z=0 ft. msl
where South K=1000 ft/day = 400,000,000 sq.ft./day
where North K= 0.1 ft/day = 40,000 sq.ft./day
Horizontal flow boundaries = 895
Horizontal flow boundary conductance K/w = 0.0000501/day
Bottom elevation = -400 ft.
Area of recharge = 140.83 sq. mi.
Recharge = 61.60 mgd
Pumping = 6 mgd
Flow from Lower Maunalei Tunnel = 0.000 mgd
Flow from Upper Maunalei Tunnel = 0.000 mgd

MODFLOW OUPUT THROUGH SURFER GRAPH

Maximum drawdown = 942 ft.
(contour truncated at 450 ft.)

⊕ - Well locations with original water levels.

☐ - Numerical coastline of Lanai

CLOSURE CRITERIA

Maximum water level change < 0.001
Water balance < 1% (Actual = -0.05%)

Figure 47. Scenario 3 Predictive Regional Drawdown Contours

## Scenario 4: Combined *FD* Removal & 6 mgd Pumping Scenarios

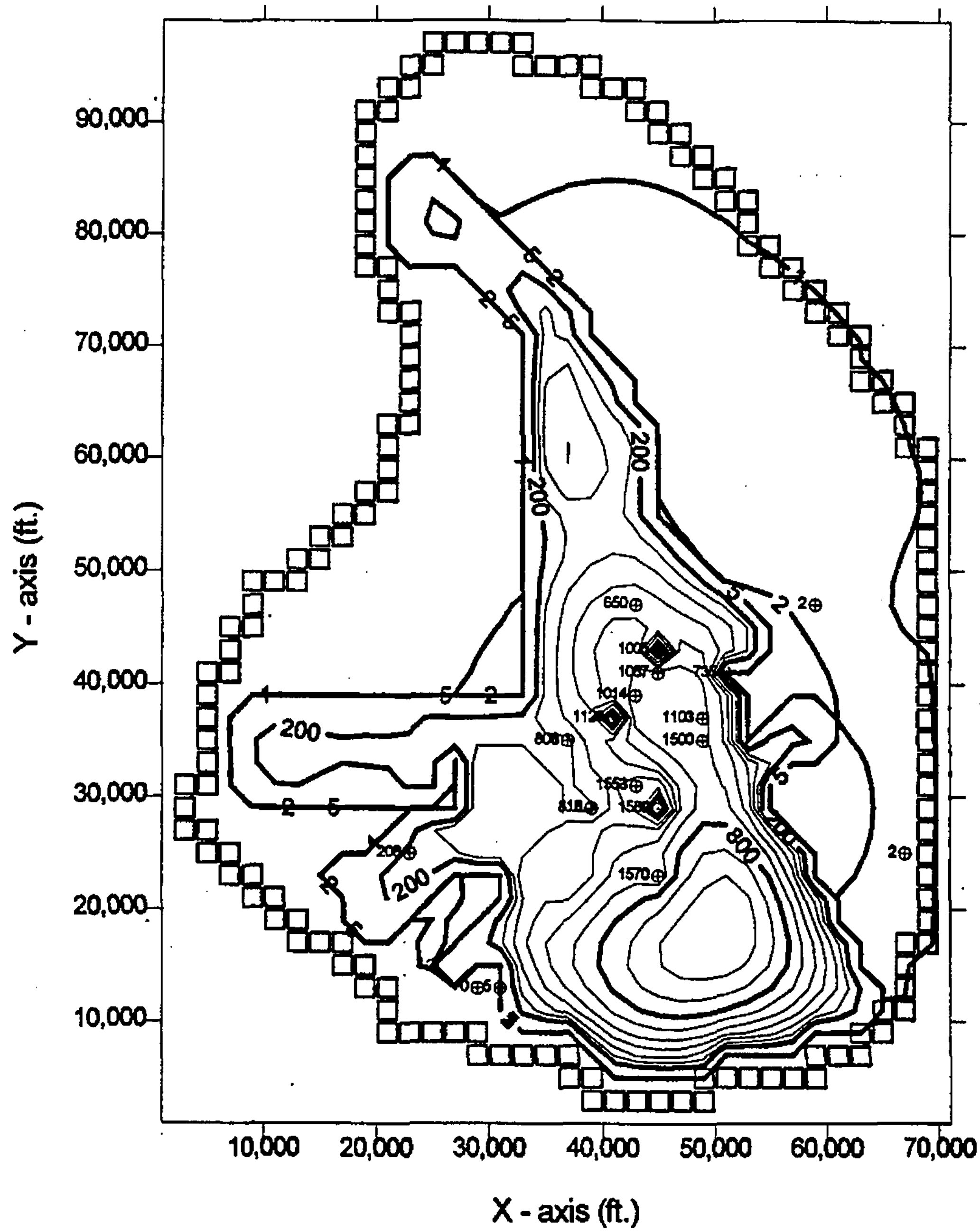
Scenario 4 is the combination of scenarios 2 & 3. Figure 48, pg. 110, shows that regional water levels are greatly affected throughout the high-level area with high drawdowns located around several existing wells. Figure 49, pg. 111, shows the spatial distribution of drawdowns with maximum regional drawdowns in excess of 1300 ft. Regional water levels would render many wells useless as they reach or go below sea level. This is not unexpected since the total stress delivered to the aquifer is equivalent to a 14 mgd pumping scenario which is over twice the next nearest sustainable yield estimate ever made for the island. However, even at this elevated pumpage scenario the model predicts regional water levels would remain near 1000 ft above sea level but on the windward side of the island only.

One technical problem with this scenario is that many cells in the model actually dry up which induce error into the results. In the particular version of MODFLOW used, once cells dry up during an iteration solution they become inactive. This, in turn, reduces transmissivities in the model which may cause error in other parts of the grid. There is a module which allows MODFLOW to re-wet a cell which has dried up during an iteration but experience with this modular package resulted in a decision to leave this particular feature out of the model. Despite this drawback, the model clearly shows that the combination of total *FD* removal combined with a 6 mgd pumping scenario results in a drastic reduction of regional water levels on the leeward side of the island.

For a different perspective, Figure 50, pg. 112, was produced to compare water resulting water level responses between scenarios 2-4. Using the same A-A' profile shown earlier in Figure 36, pg. 86, profiles were constructed along this base profile line to compare scenarios 2-4. As can be seen in Figure 50, greatest changes occur near the center of the island where the majority of recharge is concentrated. As one moves away from the center of the island water level responses become more attenuated, especially when one moves outside the high-level area and into the basal portions of the island's ground water system.

# Simulated Regional Steady-State Ground-Water Level Contours for La

**Existing Wells Pumped to 6 mgd & Fog Drip Removed**




MODFLOW INPUT DATA

Storage Coeffcient. = 0 (i.e. non-transient)
Global Kh = 1000 ft/d
Caldera Kh = 100 ft/d
River conductance Kl w/m
  with lw=4,000,000 sq.ft.,m=100 ft.,@ z=0 ft. msl
  where South K=1000 ft/day = 400,000,000 sq.ft./day
  where North K= 0.1 ft/day = 40,000 sq.ft./day
Horizontal flow boundaries = 895
  Horizontal flow boundary conductance K/w = 0.0000501/day
Bottom elevation = -400 ft.
Area of recharge = 140.83 sq. mi.
Recharge = 53.1 mgd
Pumping = 6 mgd (4.2 - some wells go dry)
Flow from Lower Maunalei Tunnel = 0.000 mgd
Flow from Upper Maunalei Tunnel = 0.000 mgd

MODFLOW OUPUT THROUGH SURFER GRAPHIC

Maximum water level = 1096 ft. above mean sea le
(contour truncated at 1000 ft. above msl)

⊕ - Well locations with original water levels.

☐ - Numerical coastline of Lanai

CLOSURE CRITERIA

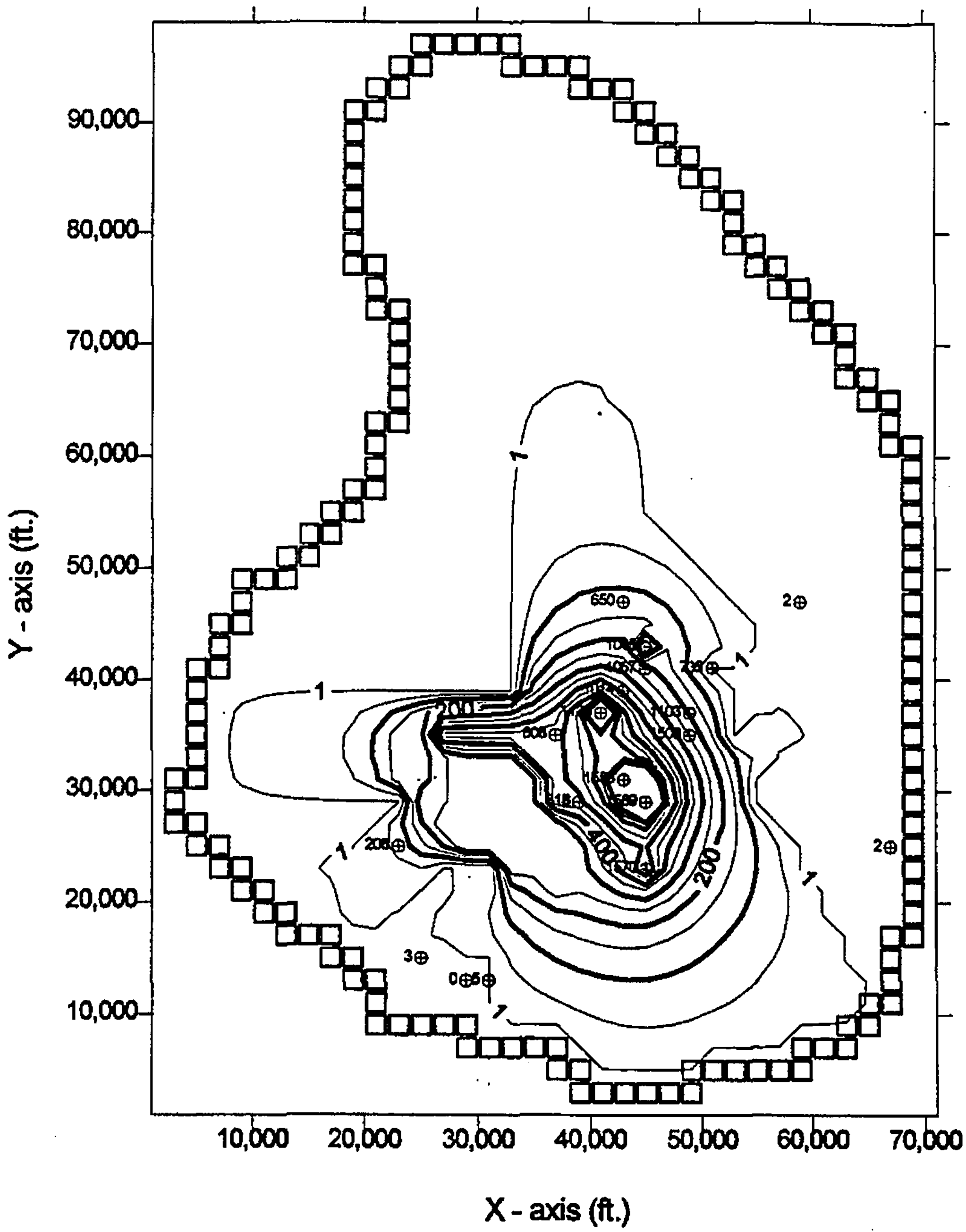
Maximum water level change < 0.001
Water balance < 1% (Actual = -0.05%)

1

Figure 48. Scenario 4 Predictive Regional Ground-Water Level Contours

## Simulated Regional Steady-State Drawdown Contours for Lanai

**Existing Wells Pumped to 6 mgd & Fog Drip Removed**




MODFLOW INPUT DATA

Storage Coeffcient. = 0 (i.e. non-transient)
Global Kh = 1000 ft/d
Caldera Kh = 100 ft/d
River conductance Klw/m
with lw=4,000,000 sq.ft.,m=100 ft.,@ z=0 ft. msl
where South K=1000 ft/day = 400,000,000 sq.ft./day
where North K= 0.1 ft/day = 40,000 sq.ft./day
Horizontal flow boundaries = 895
Horizontal flow boundary conductance K/w = 0.0000501/day
Bottom elevation = -400 ft.
Area of recharge = 140.83 sq. mi.
Recharge = 53.1 mgd
Pumping = 6 mgd (4.2 as some wells go dry)
Flow from Lower Maunalei Tunnel = 0.000 mgd
Flow from Upper Maunalei Tunnel = 0.000 mgd

MODFLOW OUPUT THROUGH SURFER GRAPHICS

Maximum drawdown = 1309 ft. above mean sea level.
(contour truncated at 700 ft.)

⊕ - Well locations with original water levels.

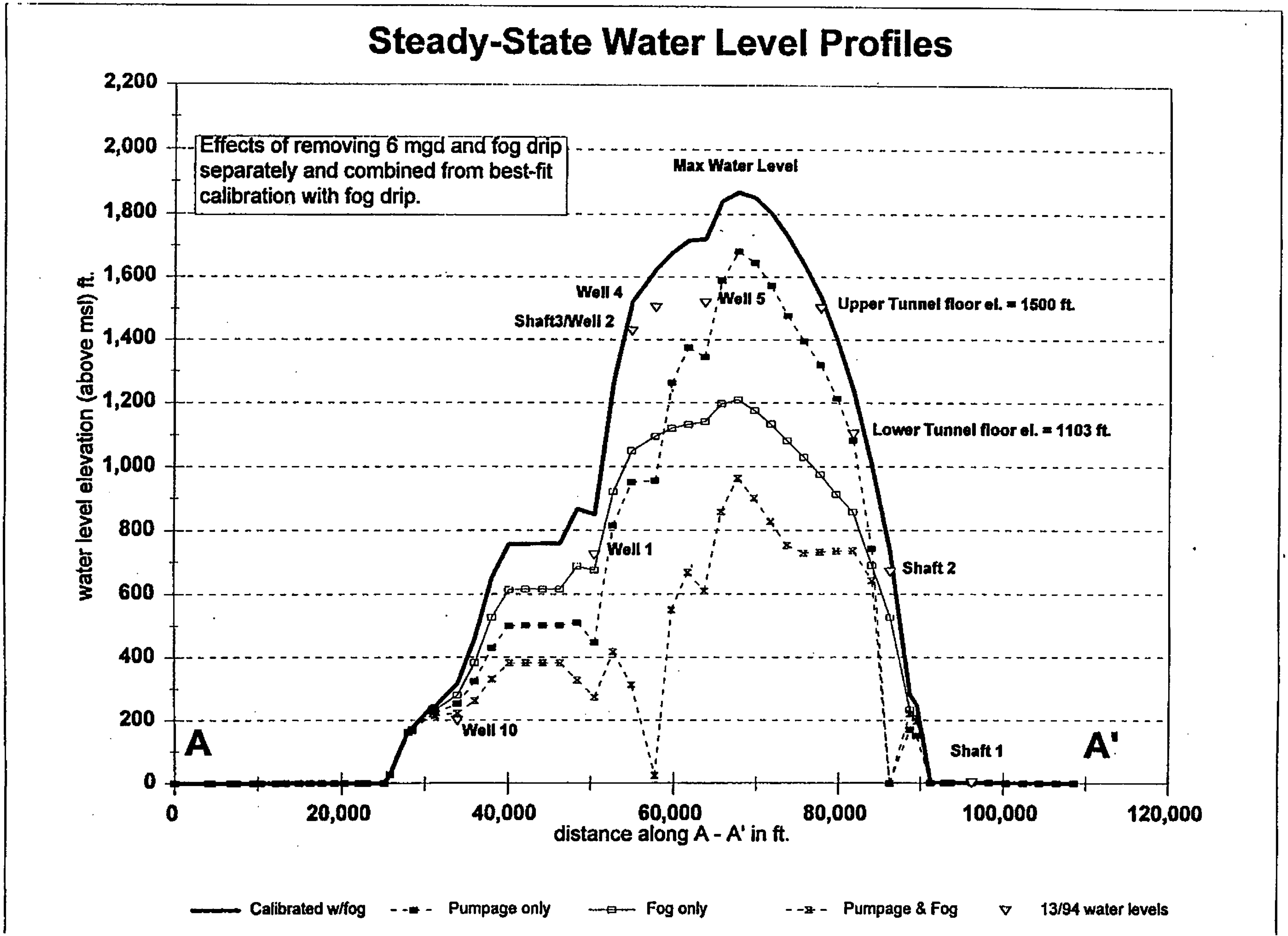
□ - Numerical coastline of Lanai

CLOSURE CRITERIA

Maximum water level change < 0.001
Water balance < 1% (Actual = -0.05%)



Figure 49. Scenario 4 Predictive Regional Drawdown Contours



Steady-State Water Level Profiles
Effects of removing 6 mgd and fog drip separately and combined from best-fit calibration with fog drip.
Max Water Level
Well 4
Well 5
Shaft3/Well 2
Upper Tunnel floor el. = 1500 ft.
Lower Tunnel floor el. = 1103 ft.
Well 1
Shaft 2
Well 10
Shaft 1
A
A'
water level elevation (above msl) ft.
distance along A - A' in ft.
2,200
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
0
20,000
40,000
60,000
80,000
100,000
120,000
Calibrated w/fog
Pumpage only
Fog only
Pumpage & Fog
13/94 water levels

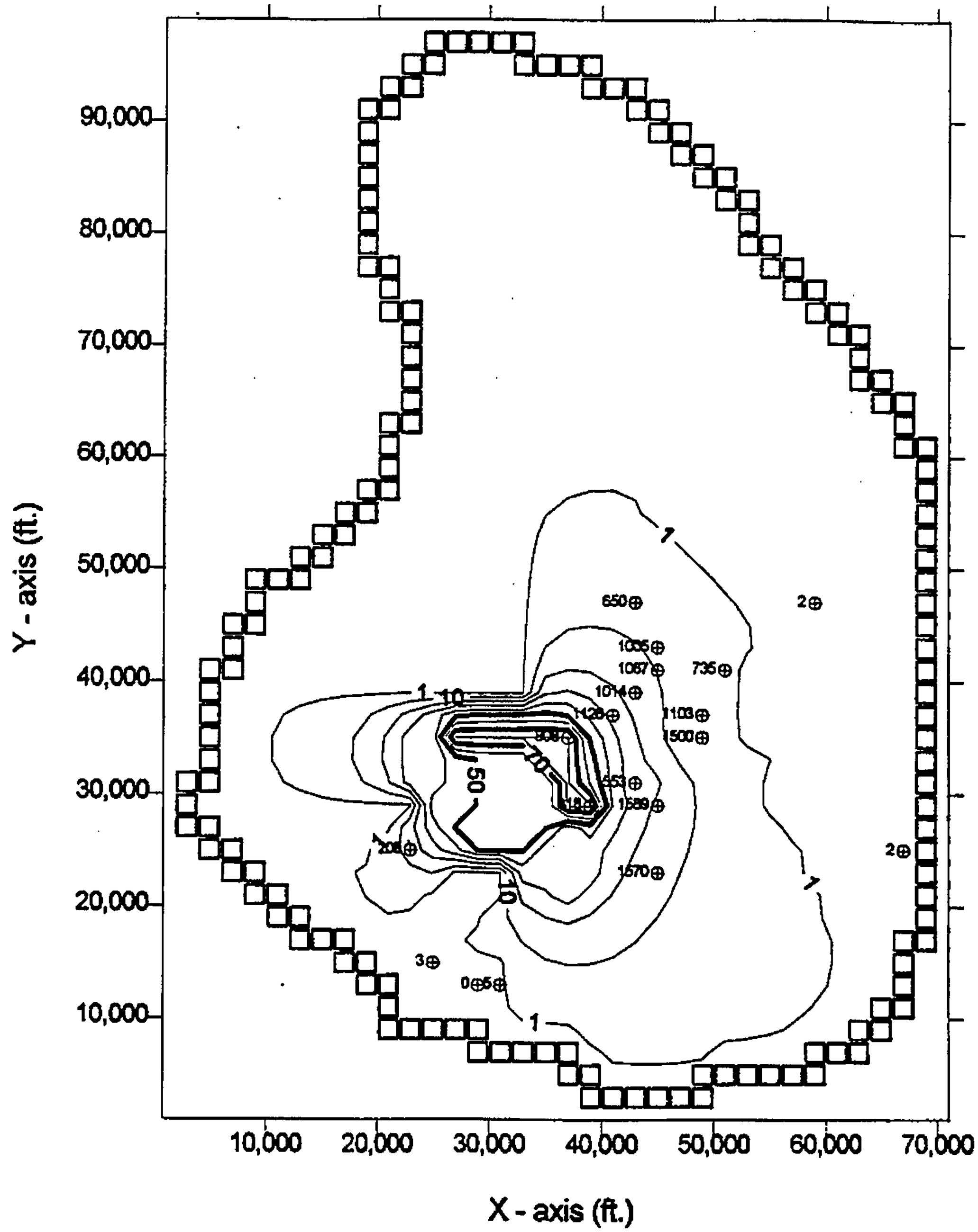
## Scenario 5: Palawai Caldera Pumpage Impacts

This scenario is based on the concern over the impact of pumping wells 1 & 9 (and the soon to be completed Well 14). Chlorides in Well 1 have decreased with increasing pumpage which indicates that fresher water is being supplied to the well and raises concern over the impact on upgradient sources.

Figure 51, pg. 114, shows the steady-state drawdown contours associated with pumping just wells 1 & 9 to assess their impact on the aquifer. To filter out effects of other well pumpage all other wells are turned off for this scenario. As can be seen, in the caldera region a total pumpage of 0.650 mgd would have a regional drawdown of about 50 ft with a maximum drawdown of about 80 ft. Other wells upgradient would see steady-state regional drawdowns of about 10 to 30 ft. due to the caldera pumpage. Given the general sensitivity of the high-level wells to local pumpage and climactic events it would not be unreasonable "miss" effects of the caldera pumpage. In other words, the relative effect of caldera pumpage is such that pumpage and the climate would have to be very steady over a reasonable long period to measure the effects of caldera pumpage in upgradient sources. Also, sensitivity analysis (see Figure 39, pg. 95) has shown that the model is insensitive to caldera permeability, probably due to the small region it covers compared to the entire island. Generally speaking, the model predicts that the effects of caldera pumpage on upgradient well regional water level are relatively small.

## Simulated Regional Steady-State Drawdown Contours for La

### Caldera Pumpage Effects Only




MODFLOW INPUT DATA

Storage Coeffcient. = 0 (i.e. non-transient)
Global Kh = 1000 ft/d
Caldera Kh = 100 ft/d
River conductance Klw/m
with lw=4,000,000 sq.ft.,m=100 ft.,@ z=0 ft. msl
where South K=1000 ft/day = 400,000,000 sq.ft./day
where North K= 0.1 ft/day = 40,000 sq.ft./day
Horizontal flow boundaries = 895
Horizontal flow boundary conductance K/w = 0.0000501/day
Bottom elevation = -400 ft.
Area of recharge = 140.83 sq. mi.
Recharge = 61.60 mgd
Pumping = 0.650 mgd (caldera only)
Flow from Lower Maunalei Tunnel = 0.256 mgd
Flow from Upper Maunalei Tunnel = 0.036 mgd

MODFLOW OUPUT THROUGH SURFER GRA

Maximum drawdown = 82 ft.
(contour truncated at 80 ft.)

⊕ - Well locations with original water levels.

□ - Numerical coastline of Lanai

CLOSURE CRITERIA

Maximum water level change < 0.001
Water balance < 1% (Actual = -0.05%)

Figure 51. Scenario 5 Predictive Regional Drawdown Contours

## Scenario 6: A Potential Plan of Future Pumpage

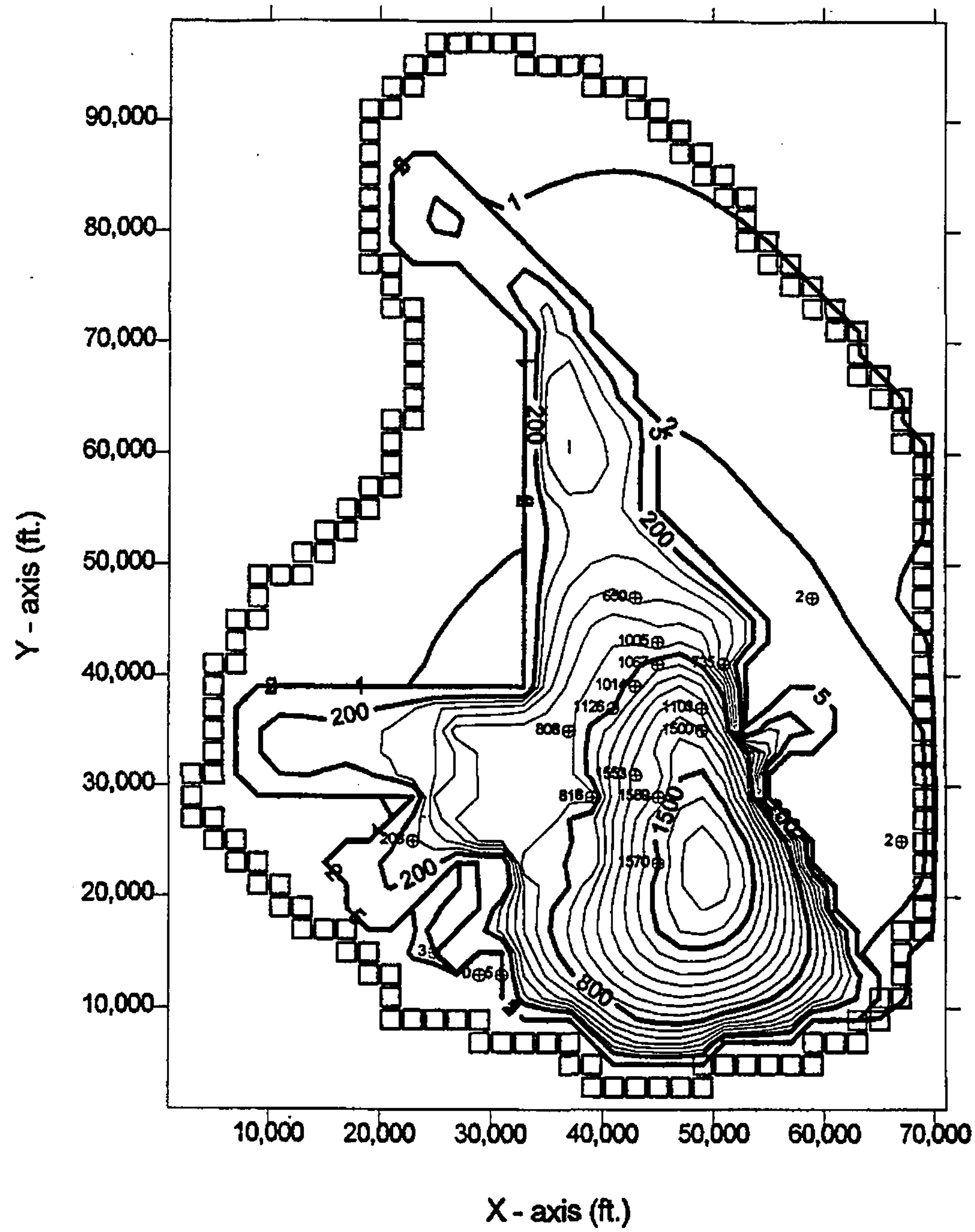
The pumpage distribution for this scenario has been supplied by LCo. which should provide a more realistic pumping scenario for the future. The pumpage scenario is only a possible distribution of average pumping at each existing source with the new addition of Well 14 (State Well No. xxxx-xx) which is near completion as of this writing.

Results of this pridictive run are shown graphically in Figures 52 & 53 on the following pages.

As expected, the resulting regional water levels fall between the extremes of long-term pumping and scenarios 2, 3, and 4.

# Simulated Regional Steady-State Ground Water Level Contours for Lan

Existing Wells Pumped to 3.520 mgd




MODFLOW INPUT DATA

Storage Coeffcient. = 0 (i.e. non-transient)
Global Kh = 1000 ft/d
Caldera Kh = 100 ft/d
River conductance Klw/m
  with lw=4,000,000 sq.ft.,m=100 ft.,@ z=0 ft. msl
  where South K=1000 ft/day = 400,000,000 sq.ft./day
  where North K= 0.1 ft/day = 40,000 sq.ft./day
Horizontal flow boundaries = 895
  Horizontal flow boundary conductance K/w = 0.0000501/day
Bottom elevation = -400 ft.
Area of recharge = 140.83 sq. mi.
Recharge = 61.60 mgd
Pumping = 3.520 mgd
Flow from Lower Maunalei Tunnel = 0.103 mgd
Flow from Upper Maunalei Tunnel = 0.000 mgd

MODFLOW OUPUT THROUGH SURFER GRAPHIC

Maximum water level = 1761 ft. above mean sea lev
(contour truncated at 1700 ft. above msl)

⊕ - Well locations with original water levels.

□ - Numerical coastline of Lanai

CLOSURE CRITERIA

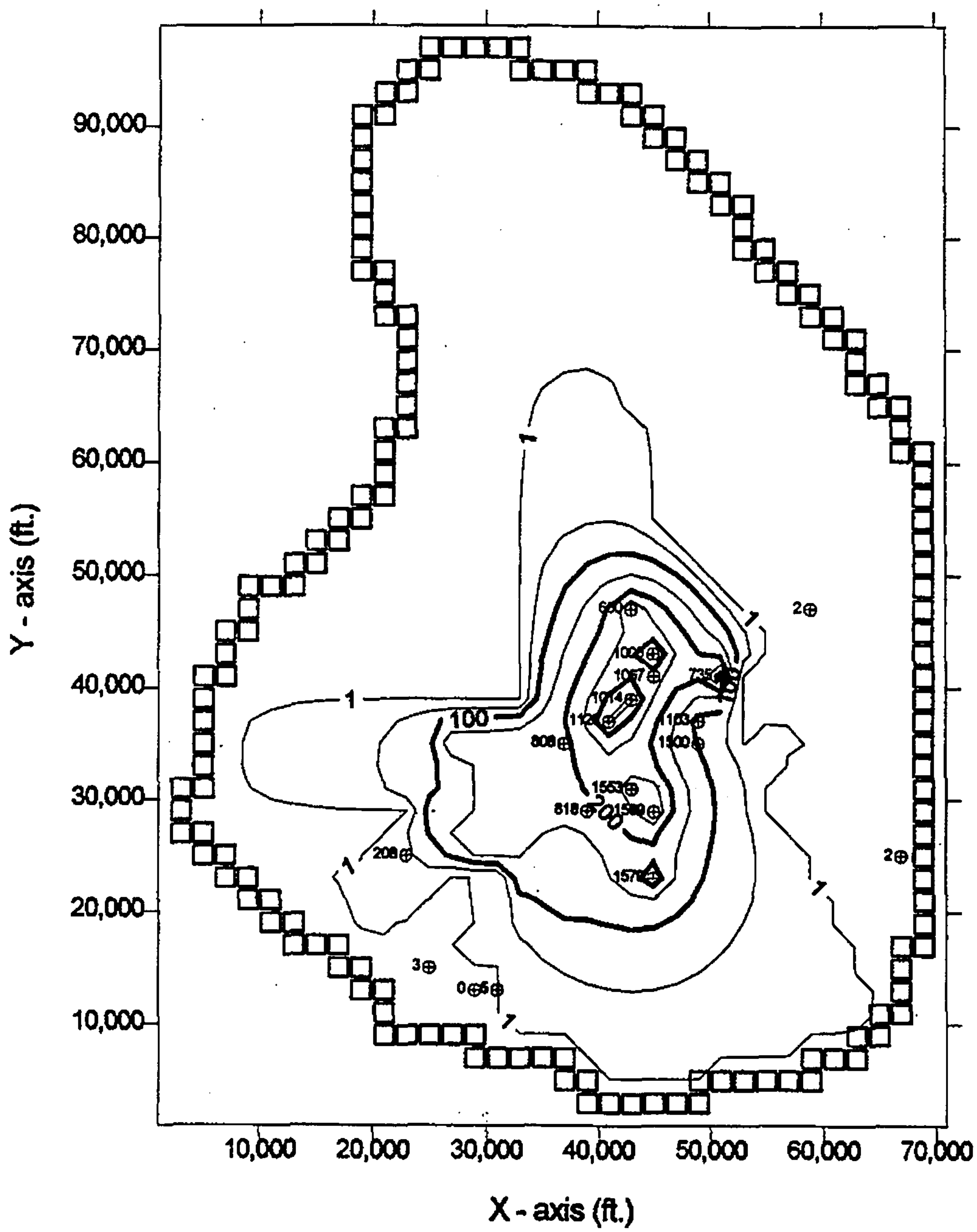
Maximum water level change < 0.001
Water balance < 1% (Actual = -0.05%)



Figure 52. Scenario 6 Predictive Regional Ground-Water Level Contours

Simulated Regional Steady-State Drawdown Contours for Lanai

**Best-Fit Calib[illegible]ion with Existing Wells Pumped at [illegible]0 mgd**




MODFLOW INPUT DATA

Storage Coeffcient = 0 (i.e. non-transient)
Global Kh = 1000 ft/d
Caldera Kh = 100 ft/d
River conductance Klw/m
with lw=4,000,000 sq.ft.,m=100 ft.,@z=0 ft. msl
where South K=1000 ft/day = 400,000,000 sq.ft./day
where North K= 0.1 ft/day = 40,000 sq.ft./day
Horizontal flow boundaries = 895
Horizontal flow boundary conductance K/w = 0.0000501/day
Bottom elevation = -400 ft.
Area of recharge = 140.83 sq. mi.
Recharge = 61.60 mgd
Pumping = 3.520 mgd (Lanai Co.)
Flow in Lower Maunalei Tunnel = 0.103 mgd
Flow in Upper Maunalei Tunnel = 0.000 mgd

MODFLOW OUPUT THROUGH SURFER GRAPHICS

Maximum drawdown =360 ft. from long term steady-state.
(contour truncated at 350 ft.)

⊕ - Well locations with original water levels.

□ - Numerical Coastline of Lanai

CLOSURE CRITERIA

Maximum water level change < 0.001
Water balance < 1% (Actual = -0.05%)



Figure 53. Scenario 6 Predictive Regional Drawdown Contours

## Summary of Predictive Scenario Results

Table 24 below summarizes the steady-state results for individual wells for the vario predictive runs rather than the island profiles shown earlier. The reader is reminded that the be: fit aquifer parameters found in Table 16, pg. 81 are the base upon which the various stress scen ios are imposed. It is important to realize that the water levels predicted are regional and are mc relevant to the aquifer water level response rather than the actual pumping water level response each well for reasons explained earlier. Also, the reader is reminded that transient analyses h shown that there are definitely heterogeneities at the local well scale (see Table 22, pg. 93) whi also add to the uncertainty water levels in actual well sites.

### Table 24. Summary of Predictive Ground-Water System Responses

| Source | Steady-State Water Level Elevation above mean sea level in ft. | | | | | | |
|---|---|---|---|---|---|---|---|
| | Highest Observed Period 13 1994 | Scenario | | | | | |
| | | 1 '42-'94 Ave | 2 No Fog-Drip | 3 Pump 6 mgd | 4 6 mgd & no FD | 5 Palawai Caldera only | 6 Lana |
| Shaft 2 | 681 | 627 | 527 | -204 | < -400 | 735 | |
| Well 1 | [a]729 | 765 | 675 | 449 | 275 | 768 | |
| Well 2/Shaft 3 | 1426 | 1259 | 1050 | 953 | 315 | 1502 | |
| Well 3 | 1024 | 974 | 861 | 412 | < -400 | 1127 | |
| Well 4 | 1503 | 1390 | 1096 | 957 | 26 | 1606 | |
| Well 5 | [b]1519 | 1604 | 1143 | 1345 | 608 | 1709 | |
| Well 6 | 1026 | 915 | 764 | 190 | < -400 | 983 | |
| Well 9 | 721 | 762 | 672 | 447 | 275 | 764 | |
| | Steady-State Tunnel Gravity Flow in mgd | | | | | | |
| Upper Tunnel | 0.005 | 0.183 | 0.000 | 0.000 | 0.000 | 0.000 | |
| Lower Tunnel | [c]0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | |

a. As of October 1994
b. As of November 1993
c. As of January 1991

A descriptive summary of results for each scenario which considers transient results of each predictive run is as follows:

1. Long-term pumpage is between 20% to 95% complete in terms of present water level change compared to steady-state water level change. However, Upper Maunalei Tunnel is predicted to cease flowing at continued long-term pumping.
2. Total removal of fog-drip has a more impact on water levels in the high-level aquifer area than long-term pumpage. Fog-drip, or whatever phenomena accounts for precipitation above observed rainfall, has a major role in observed water levels.
3. Pumping 6 mgd from existing sources has a greater affect than if fog-drip alone stopped altogether. However, pumpage patterns would have to be modified as under this scenario's distribution Shaft 2 may become useless. Still, it may be possible to develop 6 mgd from the aquifer without harming the resource although not without major modifications to existing wells, additional wells development, and carefully managed pumping distributions and schedules.
4. Pumping to 6 mgd and losing all fog-drip would result in several existing wells to become useless and both tunnels to cease flowing.
5. Caldera impacts to upgradient wells are relatively small.
6. It appears this pumpage scenario amongst existing wells will not harm the aquifer. However, some changes in the existing well infrastructure may still be necessary as some of the wells specified for future pumping have no track record of water level response to such stresses. The lower Maunalei Tunnel should continue to flow with an average flow of 0.103 mgd. However, the model predicts that the Upper Maunalei Tunnel would cease to flow.

## Prediction Sensitivity Analysis

No predictive sensitivity analysis was performed outright due to time constraints. Inste: it is anticipated and most probable that the model will have the same sensitivity to the horizon flow boundaries and recharge as found in earlier sensitivity analyses. However, it is evident t the distribution of pumpage is an important factor in resulting ground water level respon: according to the numerical model.

## Model Limitations

The limitations of the model are based upon the assumptions and uncertainties associa with the construction and calibration of the model. These assumptions and uncertainties do invalidate the model but do provide important caveats which should be kept in mind when int preting the results of the model. A synopsis for the assumptions and uncertainties which w described in the body of this report are listed as follows:

### SUMMARY OF ASSUMPTIONS AND UNCERTAINTIES

1. The Lana'i ground-water model is classified as an identification or "inverse" type proble Inverse type problems are where stresses, like pumpage, and the resulting responses, resulting water levels, are known, but the aquifer system is unknown. Unfortunate inverse type problems do not have unique solutions, and especially when the model i "simplified" or "effective average" version of the real world. Additionally, the "inver problem must be solved before a prediction problem can be solved (Bear,& others, 199

2. Sources of error can originate in the conceptual model, the numerical analysis, and input data. Errors in these three general areas are cumulative. Additionally, it is hard differentiate errors between the three once they are integrated.

3. Conceptual errors could arise if significant perched conditions exist on Lana'i since model does not consider this possibility. Additionally, the model does not consider t differences in the ground-water fluid from the geothermal activity in the Palawai Basin

4. Numerical errors arise mainly from the interpolation of nodal values which for Lanai's c are water levels. Ideally, actual data values should coincide with nodal location. In model cell areas cover one-quarter of a square mile and wells are not exactly located at node of the cell. This type of interpolation error can be as much as 10 ft. or more (Ander & others, 1992).

5 Another source of error is the GIS recharge calculation based on geographic informati There are over ten (10) sources of error associated with the accurate projection of any m However, since the island of Lana'i is relatively small this cartographic error is assume be small. Also, the GIS is an improvement over earlier studies which were based outdated projections.

6. For any field measured data input (head, rainfall, evaporation, recharge, etc.) sources of error include transient effects, measurement technique, scaling effects.

7. Must be aware that there are differing structures at different scales. The Lana'i ground-water model is looking at the entire island scale which may differ from the smaller scale of individual localized well sites and results from their pump tests. Such "scaling-up" may be erroneous.

8 Regional homogeneity and isotropy is assumed for the regional scale of the island which may or may not be invalid.

9. Setting boundary conditions is the area most prone to serious error. Many unknown dike boundary locations may render uniform distribution of "effective" barriers to horizontal-flow erroneous. Boundary effects of faulting are not accurately known. They could provide either an impediment or a more permeable conduit in some local situations.

10. Dike inclinations or dips are assumed to be vertical. This is not usually the case in Hawaiian volcanics as evidenced by dike systems examined in Windward Oahu and Kilauea, Hawaii.(Walker, 1987). This could invalidate single layer approach of the model.

11. Rates and spatial variations and conditions of leakage between boundaries are unknown.

12. Effects of geothermal activity on water viscosity, density, and water levels in the Palawai Basin, or elsewhere, are not directly addressed. Density in MODFLOW is assumed constant. Realistically, however, effects of this on water levels are probably less than 0.6%.

13. Resistivity analysis is of limited value since analysis is generally limited to a depth of 150 ft.(AWWA, 1973) and the presence of dikes and faults may invalidate interpretive results. Additionally, thickness and resistivity of interpreted layers are not independently well determined by resistivity analysis; only the product of the two. On the other hand, it may mean that the Ghyben-Herzberg relationship may not be applicable to the high-level water on Lana'i.

14. It is important to understand that it is the combination of dikes, faults, and rock contained within the dike complex which is most important rather than the individual hydrologic characteristics of each compartment. This is an argument, of course, for the simplified conceptual formulation of the model.

15. Variability of areal distribution (spatial heterogeneity) and annual averages based on monthly variability (temporal variability) for total rainfall, ***RF***, fog-drip, ***FD***, direct runoff, ***DRO***, changes in soil-storage, $\Delta SMS$, and evapotranspiration, ***ET***, to calculate recharge, ***R***, introduces more complexity, hence chance for subjective error.

16 Assuming maximum root-zone information is uniform throughout soil areas may induce significant error in actual evapotranspiration, $ET_a$, estimates for calculating individual cell recharge values.

17 Irrigation return, ***IR***, was ignored in calculating cell-by-cell recharge values.

18 Direct surface runoff, ***DRO***, constrained within topographical depressions is nc considered. Although preliminary GIS analysis indicates that this does not appear t induce a major significant error (underestimation) of recharge, ***R***, in the Palawai basin are the cumulative effects of island-wide depressions are unknown.

19 Pineapple reduces evapotranspiration, ***ET***, rates by about 20% (Ekern, 1960) but is ignorec

20 Pan evaporation is assumed to equal potential evapotranspiration, which is technicall incorrect.

21 Direct measurements for actual evapotranspiration, $ET_a$, and direct runoff, ***DRO***, ar lacking and must be estimated indirectly through soil-storage, $\Delta SMS$, information whic has limited actual data sampling.

22 Although the boundaries in this model may be good under steady-state conditions they ma not hold true under transient (i.e. pumping) conditions (Anderson, & others, 1992). Unde transient conditions initial hydrologic boundaries may change in response to stresse imposed under transient conditions which will result in errors. This is especially true wher the bottom of the aquifer on Lana'i is defined by the water level dependent Ghyber Herzberg relationship.

23. Variability in pumpage from well to well and year to year.

24. The model's domain and aquifer matrix are based on the entire island and pumping te analyses performed on the island. Assumptions for methods of determining global T, K, from pumping tests on Lana'i are as follows:

a. Aquifer is homogenous and isotropic.
b. Aquifer is infinite.
c. Position and nature of aquifer boundaries.
d. Occurrence and nature of confining beds.
e. Thickness of aquifer is known.
f. Fluid is homogeneous.
g. Flow to well is uniform and horizontal only.
h. Ideally, wells are fully, not partially, penetrating into the aquifer.
i. Length of aquifer pump test period is adequate.
j. Pumping rate is constant.
k. Well losses vs. aquifer losses are known.
l. Nominal vs. effective radius of well are known.

25. As stated by others, (El-Kadi, & others, 1985, Anderson, & others, 1992) comple equivalence in hydraulic behavior between the true heterogeneous or nonuniform mediu in the field and a model's homogeneous uniform medium is obviously impossibl Therefore, overall model input values are "averaged" and not necessarily true or accura values. This is the attempt to define "effective" parameters which try to preserve observ hydraulic behaviors.

26 MODFLOW does not simulate a 2 fluid system of freshwater floating on the more dense salt water which is known to exist in basal aquifers. However, this problem should not significantly affect the ground-water flow system in the dike-confined regions of the aquifer.

27 The lack of a single "effective" regional storage coefficient, *S*, makes the validity of the initial assumptions of regional homogeneity and isotropy doubtful.

28. Evaluation of a model is based on 1) The amount, distribution, and quality of information used; 2) methods and criteria used to calibrate the model; and 3) post-auditing. Obviously, a post-audit for this model cannot occur for the next several years.

29 Due to all the previous reasons above, resulting regional water level responses cannot be directly related to localized individual wells. Individual well responses will probably be both more and less than that predicted by the numerical model.

# Conclusions and Postaudit

Due to the higher level of precision required in developing the Lana'i numerical ground water model, it has been shown that there is a wealth of historical information and hydrologi studies on the island. There are a minimum of forty-four (44) historical hydrologic and geologi studies about Lana'i and numerous hydrologic consultant reports by Anderson. Additionally Lana'i has one of the few fog-drip studies ever done in Hawaii to quantify the augmentation o rainfall precipitation at higher elevations. Most importantly, there is a long record (over 50 years of rainfall, pumpage, and both pumping and non-pumping water level data which is unique in it the island-wide completeness in Hawaii. This fact is important since other hydrologists hav argued that numerical models are many times invalid since they are not 'closed' system (Oreskes, & others, 1994). Since the entire island of Lana'i is modelled with much of the historical data known it is as 'closed' a system one may find in Hawaii and may be an important contributing factor to the model's success of matching regional ground water level responses.

Despite all the possible sources of error, pitfalls, and lack of data associated with numerical models in general, the Lana'i numerical model does a reasonably good job of reproducing th observed ground-water behavior with reasonable flow parameters based on the existing data an similar information from other studies in Hawaii. The assumed steady-state ground-water level and tunnel flow data was calibrated with an excellent match and other ground-water levels for thi situation seemed reasonable on a regional scale. Also, the numerical model does a reasonabl good job at simulating the major ground water level trends observed in transient well data. However, on the local scale the model does not match actual water levels any better than 48 ft based o the mean absolute error, although this is relatively minor given the high water levels for mos wells. The transient simulations and the inability to utilize a single global storage coefficient als testify that localized water level responses are difficult to match as evidenced by transien responses in Shaft 3/Well 2 and Well 5. These difficulties do not even consider the additiona complications of including well inefficiencies. The issue is one of precision vs. accuracy; th numerical modelling effort has scrutinized Lanai's ground-water flow system at a high level c detail and precision but it is not necessarily accurate. The higher level of precision than previou studies gives one greater confidence in the recharge and conceptual make-up of the island, but th localized conditions are such that the assumptions of homogeneity and isotropy are limited to th regional scale of the island. Still, these simple island-wide assumptions and approach enabled th model to match the observed data reasonable well. The advantage of the regional assumptions i that it simplifies the model to a point where hydrologists can agree upon a simplified conceptu model, which can then be 'effectively' calibrated, and agree to disagree on how closely th numerical model represents the actual 'reality' at the localized scale. Ignoring this approac would open the model up to much more subjectivity and lead to a greater multitude of non-uniqu solutions which were initially sought to be constrained by the assumptions of homogeneity an isotropy.

It is believed by many prominent hydrologists that the true value of numerical models a the insights into how an aquifer flow system works (Anderson, 1994; Bredehoeft, 1994, 199 Konikow, 1994). This study has provided a few from which several conclusions can be draw Beginning with the source of ground water, it is clear that the estimated ground water recharge the entire island is more than previously estimated. Both the GIS and the calibrated numerical model analysis in this study support this conclusion. The long-term average recharge estimate for Lana'i is approximately sixty (60) mgd which includes fog-drip, or whatever phenomena is augmenting rainfall precipitation, above the 2000' elevation.

With the given mathematical and internal boundaries and island-wide assumptions for the conceptual model of Lana'i, the calibrated hydraulic parameters magnitudes from Table 17, pg. 82 are consistent with previously estimated values. This gives an added level of confidence to the Lana'i conceptual model as the other studies and Lana'i pumping test data analyses fall within reasonably similar orders of magnitude. Of course, the calibrated hydraulic parameter magnitudes will change as boundary conditions are modified. In areas with many unseen internal boundaries, such as Lana'i, this emphasizes the non-uniqueness of the numerical model solution. Ultimately, the statistical error between simulated and observed water levels is approximately a mean average error of 50 ft and a standard deviation of 70 ft in the high level aquifer.

The the insight provided through sensitivity analysis clearly shows that under natural conditions both horizontal flow boundary and recharge magnitudes and their spatial distributions are the most important variables in controlling the ground water flow system on Lana'i. This conclusion has various implications. One is that the combination of these two parameters *together* is the major controlling factor which governs the observed water level responses to induced climactic and man-made stresses on the flow system rather than each of these parameters alone. This was clearly shown by the problem of Shaft 2 continually drying up until the GIS spatially distributed recharge was overlaid upon the internal system of horizontal flow boundaries. Likewise, it was difficult to match observed water levels for Well 5 any better than 150 ft error and would require changing assumptions of homogeneity in various parameter values or spatial placement of internal boundaries to reduce such error.

Since the calibrated model is sensitive to recharge then recharge should be protected and enhanced to guarantee a reliable ground water resource. The numerical model has shown the importance of fog-drip and makes a strong case for the maintenance of fog-drip efficient vegetation above the 2000' elevation. A significant portion of drawdowns observed in the wells may be attributed to changes in the forest cover in the cloudy regions above 2000' ft. This has been suggested as early as 1974 (Bowles).

Given the insights provided by calibrating the model, additional insights are provided by imposing changes in stresses on the calibrated model. The spatial distribution and magnitude of pumpage are just as important as the recharge and internal boundary structures. The reader need only be reminded of the comparative results between predictive scenario 2 (fog-drip removal) & 3 (6 mgd pumping from existing sources) where drawdowns for the latter where greater than the former despite having approximately 30% less removal of water from the aquifer to see the truth in this conclusion.

Transient analysis has provided the insight that the time required to reach steady-state conditions is on the order of a few to several centuries. Also, in terms of steady-state water levels only, the model indicates that if current conditions remain unchanged drawdowns are 20% to 95% complete although it may take many years to reach 100% average steady-state water levels.Management decisions regardless of the model's validity, or 'closeness' in representing reality.

Predictive model runs provide additional insights. First, the model predicts that the reduc tion of forest cover would affect ground water levels drastically. The model shows that man more wells would be necessary to achieve pumpages near the current CWRM sustainable yiel estimate of 6 mgd assuming that long-term recharge conditions in the regions above 2000' eleva tion remain stable. Also, modifications are probably necessary to existing well configuration t realize greater long-term development of ground water on Lana'i. It appears that more wate could be developed from the windward side of the island. This is consistent with Adams's (1968 conclusions of developing sources along the northeastern windward shores of the island althoug better quality water in the high-level aquifer is likely more inland. However, the model canno address the subject of individual well yields due to the uncertainties of localized heterogeneitie and well inefficiencies. Other published numerical modelling studies in Hawaii (Underwood, & others, 1995) have stated such information must be gained through field experience or have lim ited their predictions in water levels to areas rather than specific well sites (Eyre, & others, 1986)

Finally, there is general agreement between hydrologists that post-auditing is a necessar element of any worthwhile the modelling effort (Anderson, 1994; Bredehoeft, 1994, 1995; Koni kow, 1994, Oreskes, & others, 1994). Post-auditing is the continued recalibration of the mode with new information, thus continued data collection is absolutely necessary (Emery, 1994) Even with all the available data on Lana'i the continuation of long-term data collection is neces sary if improvements to this model are desired. Areas of data collection which could be improve on Lana'i are pan evaporation and further fog-drip analysis. The continued monthly measuremen and reporting of long-term well pumpages and pumping and non-pumping water levels is als necessary to contribute to any post-auditing effort. Additionally, to address 3D concerns and geo thermal impacts additional layers and variable density fluid changes could be made to the model.

With the current drilling of Well 14, the need of post-auditing is underscored. The initia ground water level encountered is unofficial but reportedly confined and artesian conditions hav been observed. This confined situation is not considered in the current numerical model since it i only one layer. If true, this shows the need for post-auditing of model work to further fine tun this model or and any numerical model. The Lana'i numerical model is one step towards a fine tuned model but it is not the final model. Additional study could be performed to use multipl layers for a more fully three-dimensional ground-water flow model and perhaps even transpo modelling of chlorides can be performed in the future to further fine-tune a tool with which t assess natural and human induced stresses on Lanai's ground-water resource.

This report has also provided a general guideline in documenting numerical modellin efforts. There are some guidelines available in a few references (Anderson, 1994; ASTM, 199 CWRM, 1994) but none has been officially approved or endorsed by the CWRM. Guidelines a necessary to convey the assumptions, analysis, and results in a simple and consistent format.

In closing, Loucks (1995) has defined numerical models useful for management decisio as Decision Support Systems (DSS). To be useful, numerical models need to be easy to learn an remember and useful in providing information in a meaningful form (i.e. graphically) and in timely manner. The input and output methods used to design and calibrate the Lana'i model prol ably do not meet this criteria at this time, especially if post-auditing is undertaken. However, ne software is emerging which expedites this process. Information and insights gathered from th modelling effort can no doubt be used when this newer user friendly software is available.

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## Appendices

PAN & FOG · DRIP

TO BE UPDATED

Appendix A: Rainfall Data

Appendix B: GIS Monthly Recharge Results

Appendix C: Best Fit Calibration MODFLOW input files

Appendix D: Best Fit Output File from Appendix C input

Appendix E: Transient Stress Period Recharge Calculations

Appendix F: Individual Well Simulated vs. Actual Transient Water Levels

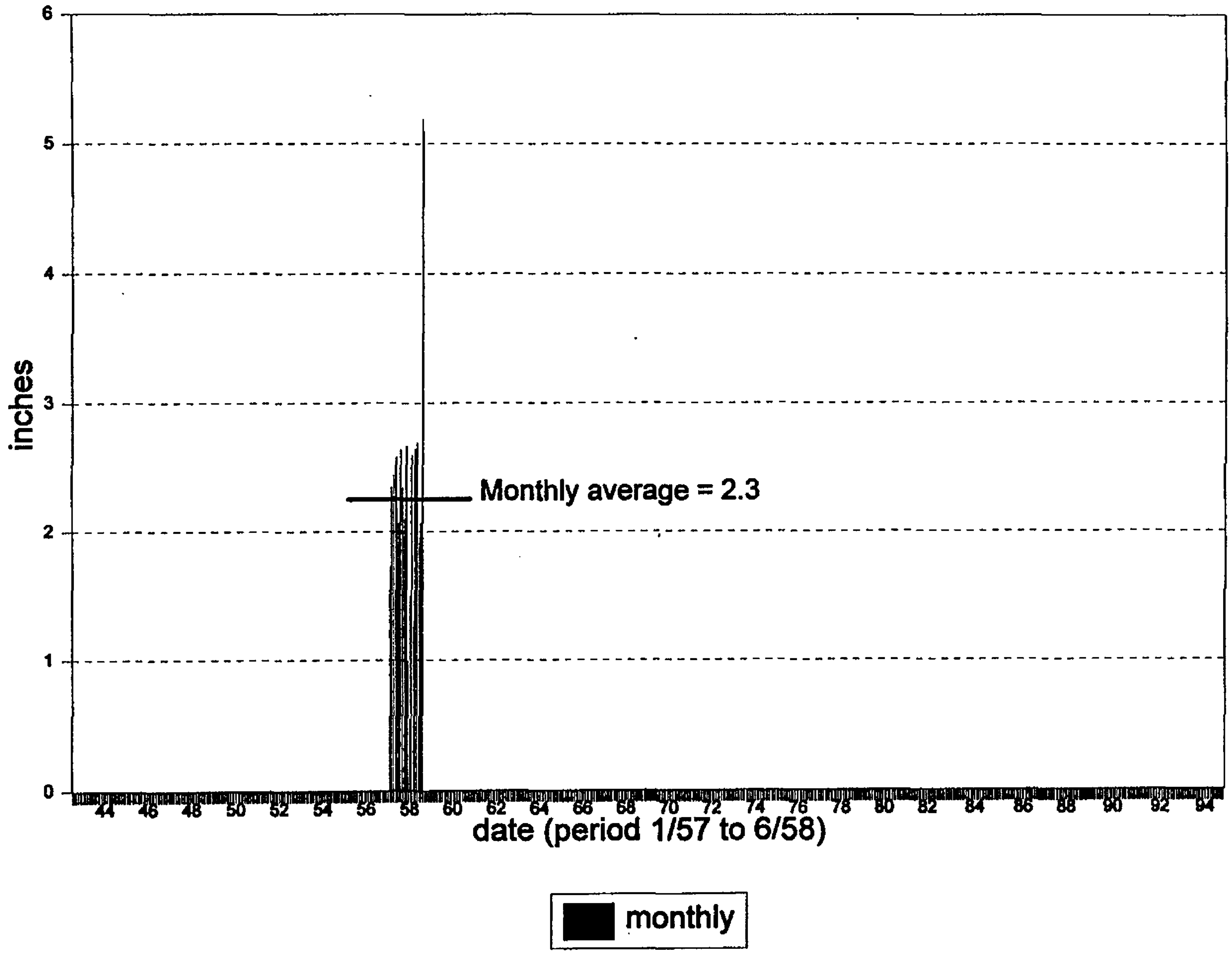
Appendix G: Individual Well Long-Term Simulated Transient Water Levels

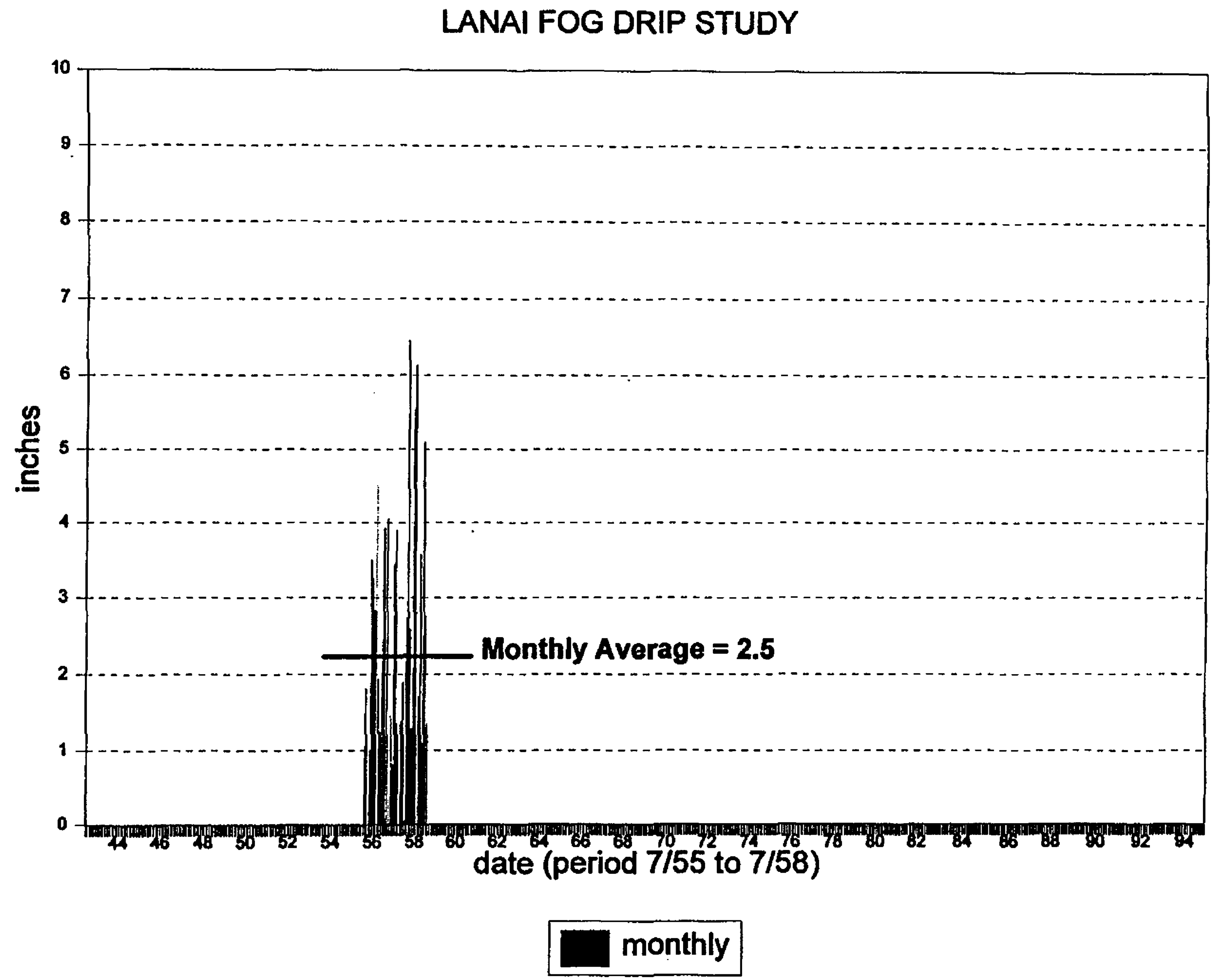
Appendix H: Individual Well Monthly Water Levels

APPENDIX A

**TO BE UPDATED**

LANAI PAN EVAPORATION DATA- STA. NO 68




LANAI FOG DRIP STUDY
inches
10
9
8
7
6
5
4
3
2
1
0
Monthly Average = 2.5
44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94
date (period 7/55 to 7/58)
monthly

APPENDIX B

**TO BE UPDATED**

# APPENDIX C

Lanai.BAS BASIC MASTER FILE PACKAGE

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C
    1    50    36    1    4
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    0     1
    5     1(25I3)              0
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0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 0 0 0 0 0 0 0
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1 1 1 1 1 1 1 1 1 1 0
0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
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-35
1.0000 1 1.0000

```
LANAI.BCF BLOCK CENTERED CONTROL PACKAGE
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1
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     0   2000.0(10E12.4)             -1    row length
     0   2000.0                  -1    col length
    11    1.000(10E12.4)              Kh
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| 0.1570E+01 | 0.1414E+02 | 0.3380E+01 | 0.5190E+01 | 0.8120E+01 | 0.7090E+01 | 0.5810E+01 | 0.4020E+01 | 0.3640E+01 | 0.7900E+01 |
| 0.9190E+01 | 0.8460E+01 | 0.7910E+01 | 0.7680E+01 | 0.1160E+01 | 0.0000E+00 | | | | |
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| 0.0000E+00 | 0.0000E+00 | 0.8320E+01 | 0.1072E+02 | 0.8150E+01 | 0.4750E+01 | 0.3540E+01 | 0.1854E+02 | 0.1873E+02 | 0.1441E+02 |
| 0.3640E+01 | 0.5080E+01 | 0.1660E+01 | 0.1001E+02 | 0.7310E+01 | 0.4910E+01 | 0.8740E+01 | 0.7280E+01 | 0.4230E+01 | 0.5650E+01 |
| 0.6190E+01 | 0.8090E+01 | 0.7440E+01 | 0.7510E+01 | 0.2520E+01 | 0.0000E+00 | | | | |
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| 0.0000E+00 | 0.1150E+01 | 0.1011E+02 | 0.9670E+01 | 0.6960E+01 | 0.6280E+01 | 0.5390E+01 | 0.1289E+02 | 0.1196E+02 | 0.2970E+01 |
| 0.1160E+01 | 0.5900E+01 | 0.9220E+01 | 0.7080E+01 | 0.1417E+02 | 0.5420E+01 | 0.4110E+01 | 0.2420E+01 | 0.1730E+01 | 0.3300E+01 |
| 0.6160E+01 | 0.7590E+01 | 0.6690E+01 | 0.7160E+01 | 0.4660E+01 | 0.0000E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 |
| 0.1000E+00 | 0.6360E+01 | 0.1055E+02 | 0.1040E+02 | 0.6330E+01 | 0.1470E+01 | 0.2010E+01 | 0.4300E+00 | 0.0000E+00 | 0.0000E+00 |
| 0.1350E+01 | 0.3390E+01 | 0.7300E+01 | 0.7580E+01 | 0.4820E+01 | 0.1490E+01 | 0.3210E+01 | 0.1120E+01 | 0.5100E+00 | 0.1380E+01 |
| 0.7210E+01 | 0.7370E+01 | 0.7470E+01 | 0.7460E+01 | 0.5810E+01 | 0.1000E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.8900E+00 |
| 0.5840E+01 | 0.1005E+02 | 0.9790E+01 | 0.8180E+01 | 0.7150E+01 | 0.5850E+01 | 0.9500E+00 | 0.1200E+00 | 0.0000E+00 | 0.0000E+00 |
| 0.1490E+01 | 0.3190E+01 | 0.8570E+01 | 0.1460E+01 | 0.2280E+01 | 0.5100E+00 | 0.1200E+00 | 0.2700E+00 | 0.2200E+00 | 0.1330E+01 |
| 0.6970E+01 | 0.8190E+01 | 0.7690E+01 | 0.7810E+01 | 0.2860E+01 | 0.1200E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.1900E+01 | 0.7570E+01 |
| 0.9230E+01 | 0.8750E+01 | 0.6840E+01 | 0.8170E+01 | 0.6710E+01 | 0.7150E+01 | 0.4910E+01 | 0.1430E+01 | 0.2000E-01 | 0.7100E+00 |
| 0.6300E+00 | 0.3580E+01 | 0.5750E+01 | 0.1300E+00 | 0.7000E+00 | 0.1200E+01 | 0.6710E+01 | 0.5230E+01 | 0.1159E+02 | 0.7440E+01 |
| 0.7250E+01 | 0.7970E+01 | 0.7280E+01 | 0.7100E+01 | 0.5930E+01 | 0.5000E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.9000E-01 | 0.2710E+01 | 0.7930E+01 | 0.8510E+01 |
| 0.9440E+01 | 0.9690E+01 | 0.7610E+01 | 0.3640E+01 | 0.4850E+01 | 0.7490E+01 | 0.8230E+01 | 0.7160E+01 | 0.2600E+01 | 0.2900E+00 |
| 0.1330E+01 | 0.6080E+01 | 0.4100E+01 | 0.1760E+01 | 0.2050E+01 | 0.1400E+00 | 0.1270E+01 | 0.3750E+01 | 0.1111E+02 | 0.9940E+01 |
| 0.1129E+02 | 0.6660E+01 | 0.7080E+01 | 0.6990E+01 | 0.6660E+01 | 0.2800E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.3540E+01 | 0.7520E+01 | 0.6510E+01 | 0.5050E+01 |
| 0.7230E+01 | 0.6730E+01 | 0.5870E+01 | 0.5870E+01 | 0.5850E+01 | 0.6550E+01 | 0.6850E+01 | 0.7730E+01 | 0.5600E+01 | 0.1930E+01 |
| 0.7590E+01 | 0.6020E+01 | 0.3350E+01 | 0.3010E+01 | 0.3130E+01 | 0.1116E+02 | 0.1116E+02 | 0.1442E+02 | 0.1650E+02 | 0.1264E+02 |
| 0.9610E+01 | 0.6490E+01 | 0.1015E+02 | 0.1176E+02 | 0.1448E+02 | 0.1060E+01 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.5800E+00 | 0.7110E+01 | 0.8030E+01 | 0.6050E+01 | 0.1910E+01 |
| 0.2410E+01 | 0.4510E+01 | 0.4330E+01 | 0.5790E+01 | 0.6360E+01 | 0.7180E+01 | 0.7680E+01 | 0.7560E+01 | 0.3060E+01 | 0.6360E+01 |
| 0.8710E+01 | 0.4620E+01 | 0.3170E+01 | 0.2710E+01 | 0.8020E+01 | 0.1460E+02 | 0.2262E+02 | 0.1709E+02 | 0.1489E+02 | 0.4540E+01 |
| 0.4450E+01 | 0.7410E+01 | 0.7800E+01 | 0.9400E+01 | 0.1104E+02 | 0.3700E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.4690E+01 | 0.8660E+01 | 0.6840E+01 | 0.7480E+01 | 0.6110E+01 |
| 0.4040E+01 | 0.3740E+01 | 0.4550E+01 | 0.5170E+01 | 0.5620E+01 | 0.7460E+01 | 0.7760E+01 | 0.5890E+01 | 0.2880E+01 | 0.6360E+01 |
| 0.9200E+01 | 0.4940E+01 | 0.5560E+01 | 0.2490E+01 | 0.4080E+01 | 0.4540E+01 | 0.2103E+02 | 0.1034E+02 | 0.7490E+01 | 0.6220E+01 |
| 0.4990E+01 | 0.6530E+01 | 0.1015E+02 | 0.1367E+02 | 0.1173E+02 | 0.3100E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.1270E+01 | 0.8730E+01 | 0.8840E+01 | 0.5690E+01 | 0.5470E+01 | 0.4410E+01 |
| 0.4210E+01 | 0.3430E+01 | 0.4420E+01 | 0.6010E+01 | 0.6550E+01 | 0.7120E+01 | 0.7770E+01 | 0.6680E+01 | 0.5090E+01 | 0.4420E+01 |
| 0.1410E+01 | 0.7900E+00 | 0.6430E+01 | 0.1362E+02 | 0.1143E+02 | 0.2052E+02 | 0.1758E+02 | 0.1260E+02 | 0.5670E+01 | 0.9480E+01 |
| 0.6280E+01 | 0.9390E+01 | 0.1068E+02 | 0.1098E+02 | 0.4390E+01 | 0.4000E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.6540E+01 | 0.8740E+01 | 0.7520E+01 | 0.3830E+01 | 0.3160E+01 | 0.4930E+01 |
| 0.4450E+01 | 0.4020E+01 | 0.4960E+01 | 0.6220E+01 | 0.6480E+01 | 0.7190E+01 | 0.6430E+01 | 0.7070E+01 | 0.6160E+01 | 0.3900E+00 |
| 0.0000E+00 | 0.5870E+01 | 0.1468E+02 | 0.3291E+02 | 0.3346E+02 | 0.3538E+02 | 0.1700E+02 | 0.1220E+02 | 0.1089E+02 | 0.1068E+02 |
| 0.9720E+01 | 0.1094E+02 | 0.9150E+01 | 0.8890E+01 | 0.4280E+01 | 0.3800E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.8280E+01 | 0.7330E+01 | 0.4080E+01 | 0.2960E+01 | 0.3550E+01 | 0.4830E+01 |
| 0.3750E+01 | 0.4930E+01 | 0.4690E+01 | 0.4750E+01 | 0.6110E+01 | 0.6300E+01 | 0.5920E+01 | 0.7160E+01 | 0.7470E+01 | 0.1870E+01 |
| 0.2500E+01 | 0.7740E+01 | 0.2301E+02 | 0.3675E+02 | 0.3814E+02 | 0.3341E+02 | 0.3024E+02 | 0.2513E+02 | 0.1509E+02 | 0.1275E+02 |
| 0.1090E+02 | 0.1194E+02 | 0.9280E+01 | 0.7880E+01 | 0.4880E+01 | 0.4100E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.9200E+00 | 0.1006E+02 | 0.8180E+01 | 0.4210E+01 | 0.2650E+01 | 0.3280E+01 | 0.4420E+01 |
| 0.2960E+01 | 0.4550E+01 | 0.2750E+01 | 0.4480E+01 | 0.4090E+01 | 0.2700E+01 | 0.3540E+01 | 0.7480E+01 | 0.8590E+01 | 0.7040E+01 |
| 0.1180E+01 | 0.3410E+01 | 0.2328E+02 | 0.3659E+02 | 0.3830E+02 | 0.4091E+02 | 0.3999E+02 | 0.3429E+02 | 0.2178E+02 | 0.1758E+02 |
| 0.1425E+02 | 0.1044E+02 | 0.9390E+01 | 0.9710E+01 | 0.7400E+01 | 0.5900E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.8000E-01 | 0.8580E+01 | 0.8870E+01 | 0.7340E+01 | 0.3150E+01 | 0.9700E+00 | 0.4250E+01 |
| 0.3230E+01 | 0.4890E+01 | 0.3650E+01 | 0.3400E+01 | 0.2790E+01 | 0.3780E+01 | 0.3960E+01 | 0.7310E+01 | 0.8570E+01 | 0.3740E+01 |
| 0.3030E+01 | 0.1050E+01 | 0.2108E+02 | 0.3381E+02 | 0.3667E+02 | 0.3928E+02 | 0.3837E+02 | 0.2735E+02 | 0.2154E+02 | 0.1641E+02 |
| 0.1370E+02 | 0.1020E+02 | 0.9920E+01 | 0.8550E+01 | 0.6490E+01 | 0.3800E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.1230E+01 | 0.8880E+01 | 0.9640E+01 | 0.9230E+01 | 0.6870E+01 | 0.1500E+01 | 0.2330E+01 |
| 0.3340E+01 | 0.4920E+01 | 0.3740E+01 | 0.4200E+01 | 0.4140E+01 | 0.4800E+01 | 0.7330E+01 | 0.7710E+01 | 0.8340E+01 | 0.9280E+01 |
| 0.3610E+01 | 0.1142E+02 | 0.9190E+01 | 0.3423E+02 | 0.3655E+02 | 0.3714E+02 | 0.3481E+02 | 0.3369E+02 | 0.2524E+02 | 0.1906E+02 |
| 0.1418E+02 | 0.6420E+01 | 0.8490E+01 | 0.6790E+01 | 0.7090E+01 | 0.2100E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.4080E+01 | 0.8900E+01 | 0.9030E+01 | 0.8960E+01 | 0.7050E+01 | 0.5310E+01 | 0.3580E+01 |
| 0.2500E+01 | 0.4450E+01 | 0.4900E+01 | 0.3510E+01 | 0.3260E+01 | 0.5690E+01 | 0.7270E+01 | 0.7750E+01 | 0.7920E+01 | 0.9170E+01 |
| 0.9040E+01 | 0.7930E+01 | 0.1149E+02 | 0.3351E+02 | 0.3617E+02 | 0.3619E+02 | 0.3146E+02 | 0.3333E+02 | 0.2809E+02 | 0.1881E+02 |
| 0.1329E+02 | 0.9690E+01 | 0.9920E+01 | 0.8850E+01 | 0.7960E+01 | 0.2800E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.2480E+01 | 0.6680E+01 | 0.8580E+01 | 0.8930E+01 | 0.9370E+01 | 0.8550E+01 | 0.7840E+01 |
| 0.7380E+01 | 0.4030E+01 | 0.4050E+01 | 0.2920E+01 | 0.4020E+01 | 0.5380E+01 | 0.6690E+01 | 0.7520E+01 | 0.7590E+01 | 0.7860E+01 |
| 0.8560E+01 | 0.5740E+01 | 0.1247E+02 | 0.3591E+02 | 0.3624E+02 | 0.3400E+02 | 0.3189E+02 | 0.3058E+02 | 0.2275E+02 | 0.1243E+02 |
| 0.1668E+02 | 0.1573E+02 | 0.1131E+02 | 0.8050E+01 | 0.5860E+01 | 0.6000E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.4600E+00 | 0.5130E+01 | 0.8490E+01 | 0.8860E+01 | 0.8800E+01 | 0.8060E+01 |
| 0.7570E+01 | 0.6520E+01 | 0.3110E+01 | 0.2300E+01 | 0.2900E+01 | 0.2480E+01 | 0.3790E+01 | 0.4580E+01 | 0.4360E+01 | 0.7760E+01 |
| 0.7000E+01 | 0.4010E+01 | 0.2380E+02 | 0.3314E+02 | 0.3442E+02 | 0.3402E+02 | 0.3649E+02 | 0.3057E+02 | 0.1934E+02 | 0.1442E+02 |
| 0.1067E+02 | 0.5070E+01 | 0.6900E+01 | 0.7490E+01 | 0.5060E+01 | 0.3000E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.3430E+01 | 0.8360E+01 | 0.8790E+01 | 0.8830E+01 |
| 0.8210E+01 | 0.8120E+01 | 0.8030E+01 | 0.4150E+01 | 0.2670E+01 | 0.2240E+01 | 0.2850E+01 | 0.3890E+01 | 0.4790E+01 | 0.5350E+01 |
| 0.3750E+01 | 0.2060E+01 | 0.2456E+02 | 0.3025E+02 | 0.3041E+02 | 0.3914E+02 | 0.3447E+02 | 0.2537E+02 | 0.1370E+02 | 0.1066E+02 |
| 0.8120E+01 | 0.1106E+02 | 0.1132E+02 | 0.1017E+02 | 0.2890E+01 | 0.2800E+00 | | | | |
| 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.0000E+00 | 0.3370E+01 | 0.8390E+01 | 0.8800E+01 |
| 0.9060E+01 | 0.9050E+01 | 0.8440E+01 | 0.7610E+01 | 0.4460E+01 | 0.5920E+01 | 0.3400E+01 | 0.2020E+01 | 0.1730E+01 | 0.3240E+01 |

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0.7960E+01 0.9430E+01 0.7230E+01 0.7650E+01 0.5280E+01 0.5000E-01
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LANAI.BND HORIZONTAL FLOW BOUNDARY PACKAGE

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|---|---|---|---|
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| 28 | 27 | 29 | 270.00005010 |
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LANAI.RIV RIVER PACKAGE
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     1      2     14   0.000 4.000e+08-1.000e+01
     1      2     15   0.000 4.000e+08-1.000e+01
     1      2     16   0.000 4.000e+08-1.000e+01
     1      2     17   0.000 4.000e+08-1.000e+01
     1      3     17   0.000 4.000e+08-1.000e+01
     1      3     18   0.000 4.000e+04-1.000e+01
     1      3     19   0.000 4.000e+04-1.000e+01
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     1      4     21   0.000 4.000e+04-1.000e+01
     1      4     22   0.000 4.000e+04-1.000e+01
     1      5     22   0.000 4.000e+04-1.000e+01
     1      5     23   0.000 4.000e+04-1.000e+01
     1      6     23   0.000 4.000e+04-1.000e+01
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     1     10     27   0.000 4.000e+04-1.000e+01
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     1     11     28   0.000 4.000e+04-1.000e+01
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     1     12     29   0.000 4.000e+04-1.000e+01
     1     13     29   0.000 4.000e+04-1.000e+01
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     1     46     33   0.000 4.000e+04-1.000e+01
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     1     47     30   0.000 4.000e+04-1.000e+01
     1     47     31   0.000 4.000e+04-1.000e+01
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     1     48     26   0.000 4.000e+04-1.000e+01
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| 1 | 49 | 22 | 0.000 4.000e+08-1.000e+01 |
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| 1 | 49 | 25 | 0.000 4.000e+08-1.000e+01 |
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| 1 | 46 | 15 | 0.000 4.000e+08-1.000e+01 |
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| 1 | 40 | 6 | 0.000 4.000e+08-1.000e+01 |
| 1 | 39 | 4 | 0.000 4.000e+08-1.000e+01 |
| 1 | 39 | 5 | 0.000 4.000e+08-1.000e+01 |
| 1 | 38 | 3 | 0.000 4.000e+08-1.000e+01 |
| 1 | 38 | 4 | 0.000 4.000e+08-1.000e+01 |
| 1 | 37 | 2 | 0.000 4.000e+08-1.000e+01 |
| 1 | 37 | 3 | 0.000 4.000e+08-1.000e+01 |
| 1 | 35 | 2 | 0.000 4.000e+08-1.000e+01 |
| 1 | 36 | 2 | 0.000 4.000e+08-1.000e+01 |
| 1 | 35 | 3 | 0.000 4.000e+08-1.000e+01 |
| 1 | 30 | 3 | 0.000 4.000e+08-1.000e+01 |
| 1 | 31 | 3 | 0.000 4.000e+08-1.000e+01 |
| 1 | 32 | 3 | 0.000 4.000e+08-1.000e+01 |
| 1 | 33 | 3 | 0.000 4.000e+08-1.000e+01 |
| 1 | 34 | 3 | 0.000 4.000e+08-1.000e+01 |
| 1 | 30 | 4 | 0.000 4.000e+08-1.000e+01 |
| 1 | 28 | 4 | 0.000 4.000e+08-1.000e+01 |
| 1 | 29 | 4 | 0.000 4.000e+08-1.000e+01 |
| 1 | 26 | 5 | 0.000 4.000e+08-1.000e+01 |
| 1 | 27 | 5 | 0.000 4.000e+08-1.000e+01 |
| 1 | 28 | 5 | 0.000 4.000e+08-1.000e+01 |
| 1 | 26 | 6 | 0.000 4.000e+08-1.000e+01 |
| 1 | 26 | 7 | 0.000 4.000e+08-1.000e+01 |
| 1 | 25 | 7 | 0.000 4.000e+08-1.000e+01 |
| 1 | 25 | 8 | 0.000 4.000e+08-1.000e+01 |
| 1 | 24 | 8 | 0.000 4.000e+08-1.000e+01 |
| 1 | 24 | 9 | 0.000 4.000e+08-1.000e+01 |
| 1 | 23 | 9 | 0.000 4.000e+08-1.000e+01 |
| 1 | 23 | 10 | 0.000 4.000e+08-1.000e+01 |
| 1 | 22 | 10 | 0.000 4.000e+08-1.000e+01 |
| 1 | 22 | 11 | 0.000 4.000e+08-1.000e+01 |
| 1 | 19 | 11 | 0.000 4.000e+08-1.000e+01 |
| 1 | 20 | 11 | 0.000 4.000e+08-1.000e+01 |
| 1 | 21 | 11 | 0.000 4.000e+08-1.000e+01 |
| 1 | 14 | 12 | 0.000 4.000e+08-1.000e+01 |
| 1 | 15 | 12 | 0.000 4.000e+08-1.000e+01 |
| 1 | 16 | 12 | 0.000 4.000e+08-1.000e+01 |
| 1 | 17 | 12 | 0.000 4.000e+08-1.000e+01 |
| 1 | 18 | 12 | 0.000 4.000e+08-1.000e+01 |
| 1 | 19 | 12 | 0.000 4.000e+08-1.000e+01 |
| 1 | 12 | 11 | 0.000 4.000e+08-1.000e+01 |
| 1 | 13 | 11 | 0.000 4.000e+08-1.000e+01 |
| 1 | 14 | 11 | 0.000 4.000e+08-1.000e+01 |
| 1 | 5 | 10 | 0.000 4.000e+08-1.000e+01 |
| 1 | 6 | 10 | 0.000 4.000e+08-1.000e+01 |
| 1 | 7 | 10 | 0.000 4.000e+08-1.000e+01 |
| 1 | 8 | 10 | 0.000 4.000e+08-1.000e+01 |
| 1 | 9 | 10 | 0.000 4.000e+08-1.000e+01 |
| 1 | 10 | 10 | 0.000 4.000e+08-1.000e+01 |
| 1 | 11 | 10 | 0.000 4.000e+08-1.000e+01 |
| 1 | 12 | 10 | 0.000 4.000e+08-1.000e+01 |

| | | | | |
|---|---|---|---|---|
| 1 | 4 | 11 | 0.000 | 4.000e+06-1.000e+01 |
| 1 | 5 | 11 | 0.000 | 4.000e+06-1.000e+01 |
| 1 | 3 | 12 | 0.000 | 4.000e+06-1.000e+01 |
| 1 | 4 | 12 | 0.000 | 4.000e+06-1.000e+01 |
| 1 | 3 | 13 | 0.000 | 4.000e+06-1.000e+01 |

LANAI.DRN

```
     3    -1
     3
     1    32    25    1103    255.64     lower tunnel
     1    33    25    1500   1370.00     upper tunnel
     1    33    24    1500   1370.00     extension of upper
    -1
    -1
    -1
    -1
    -1
    -1
    -1
```

LANAI.WEL CALIBRATED INITIAL STEADY-STATE

```
    22     0
    22
     1    44    16   0.000
     1    44    15   0.000
     1    43    13   0.000
     1    38    12   0.000
     1    39    23   0.000
     1    39    24   0.000
     1    38    34   0.000
     1    37    22   0.000
     1    36    23   0.000
     1    36    24   0.000
     1    35    22   0.000
     1    36    20   0.000
     1    33    19   0.000
     1    33    25   0.000
     1    32    25   0.000
     1    30    26   0.000
     1    30    23   0.000
     1    29    23   0.000
     1    27    22   0.000
     1    27    31   0.000
     1    31    22   0.000
     1    32    21   0.000
```

LANAI.WEL LONGTERM PUMPAGE

```
    22     0
    22
     1    44    16   0.000      well 13
     1    44    15   0.000      well 12
     1    43    13   0.000      manele
     1    38    12   0.000      well 10
     1    39    23-20737.6       well 5
     1    39    24   0.000      dry
     1    38    34   0.000      gay
     1    37    22   0.000      dry
     1    36    23-36483.9       well 4
     1    36    24   0.000      dry
     1    35    22-83020.8       well 2 sht 3
     1    36    20-15479.0       well 1
     1    33    19 -1570.8       well 9
     1    33    25   0.000      upper
     1    32    25   0.000      lower
     1    30    26-26190.1       sht 2
     1    30    23   0.000      T-3
     1    29    23 -3919.3       well 6
     1    27    22   0.000      well 7
     1    27    30   0.000      sht 1
     1    31    22   0.000      well 8
     1    32    21-27398.1       well 3
```

LANAI.SIP STRONGLY IMPLICIT PROCEDURE PACKAGE

```
  25000      5
 1.0000  0.001     1     1     1
```

LANAI.OC OUTPUT CONTROL PACKAGE

```
     0     0    30    40
     0     1     0     1
     1     0     1     1
```

# APPENDIX D

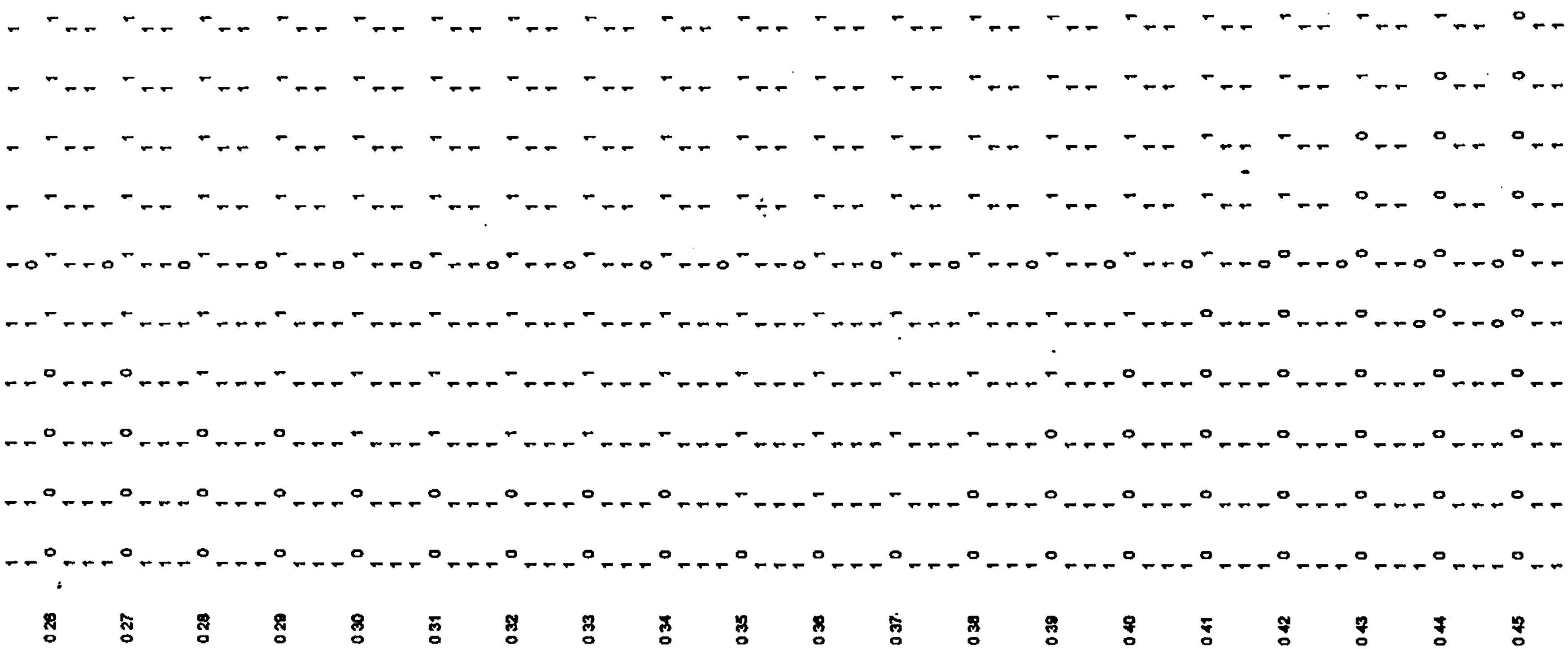
LANAI OUTPUT RESULTS (BINARY FILES ARE EXCLUDED AND USED IN CREATING REPORT FIGURES)

```
1              U.S. GEOLOGICAL SURVEY MODULAR FINITE-DIFFERENCE GROUND-WATER MODEL
0Lanai: Kh=1000, HB=895, R=61.6, P=0, K/W=5.01E-5, SC is South=4E8 North=4E4),   Khc=100,Drains (lower DC=255.8 upper DC=1370, ax
   1 LAYERS        50 ROWS        36 COLUMNS
  1 STRESS PERIOD(S) IN SIMULATION
 MODEL TIME UNIT IS DAYS
0I/O UNITS:
 ELEMENT OF IUNIT:  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
       I/O UNIT: 11 12 13 14  0  0  0 18 19  0  0 22  0  0  0 26  0  0  0  0  0  0  0  0
0BAS1 -- BASIC MODEL PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM UNIT  5
 ARRAYS RHS AND BUFF WILL SHARE MEMORY.
 START HEAD WILL BE SAVED
   16290 ELEMENTS IN X ARRAY ARE USED BY BAS
   16290 ELEMENTS OF X ARRAY USED OUT OF  350000
0BCF3 -- BLOCK-CENTERED FLOW PACKAGE, VERSION 3, 7/9/92 INPUT READ FROM UNIT 11
 STEADY-STATE SIMULATION
 CONSTANT HEAD CELL-BY-CELL FLOWS WILL BE PRINTED
 HEAD AT CELLS THAT CONVERT TO DRY=  0.00000
 WETTING CAPABILITY IS NOT ACTIVE
    LAYER  AQUIFER TYPE    INTERBLOCK T
    ------------------------------------
      1        1         0-HARMONIC
    3601 ELEMENTS IN X ARRAY ARE USED BY BCF
   19891 ELEMENTS OF X ARRAY USED OUT OF  350000
0WEL1 -- WELL PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM 12
 MAXIMUM OF   22 WELLS
      88 ELEMENTS IN X ARRAY ARE USED FOR WELLS
   19979 ELEMENTS OF X ARRAY USED OUT OF  350000
0DRN1 -- DRAIN PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM UNIT 13
 MAXIMUM OF    3 DRAINS
 CELL-BY-CELL FLOWS WILL BE PRINTED WHEN ICBCFL NOT 0
      15 ELEMENTS IN X ARRAY ARE USED FOR DRAINS
   19994 ELEMENTS OF X ARRAY USED OUT OF  350000
0RCH1 -- RECHARGE PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM UNIT 18
 OPTION 1 -- RECHARGE TO TOP LAYER
    1800 ELEMENTS OF X ARRAY USED FOR RECHARGE
   21794 ELEMENTS OF X ARRAY USED OUT OF  350000
0RIV1 -- RIVER PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM UNIT 14
 MAXIMUM OF  164 RIVER NODES
 CELL-BY-CELL FLOWS WILL BE PRINTED
     984 ELEMENTS IN X ARRAY ARE USED FOR RIVERS
   22778 ELEMENTS OF X ARRAY USED OUT OF  350000
0SIP1 -- STRONGLY IMPLICIT PROCEDURE SOLUTION PACKAGE, VERSION 1, 9/1/87 INPUT READ FROM UNIT 19
 MAXIMUM OF**** ITERATIONS ALLOWED FOR CLOSURE
  5 ITERATION PARAMETERS
  107205 ELEMENTS IN X ARRAY ARE USED BY SIP
  129983 ELEMENTS OF X ARRAY USED OUT OF  350000
0HFB1 -- HORIZONTAL FLOW BARRIER PACKAGE, VERSION 1, 06/13/86 INPUT READ FROM UNIT 26
 A TOTAL OF  895 HORIZONTAL FLOW BARRIERS
   4475 ELEMENTS IN X ARRAY ARE USED FOR HORIZONTAL FLOW BARRIERS
 134458 ELEMENTS OF X ARRAY USED OUT OF 350000
1Lanai: Kh=1000, HB=895, R=61.6, P=0, K/W=5.01E-5, SC is South=4E8 North=4E4),   Khc=100,Drains (lower DC=255.8 upper DC=1370, ax
0

                         BOUNDARY ARRAY FOR LAYER  1 WILL BE READ ON UNIT  5 USING FORMAT: (25I3)
                         ---------------------------------------------------------------------

         1      2      3      4      5      6      7      8      9     10
        11     12     13     14     15     16     17     18     19     20
        21     22     23     24     25     26     27     28     29     30
        31     32     33     34     35     36
 ..................................................................................
0 1      0      0      0      0      0      0      0      0      0      0
         0      0      0      0      0      0      0      0      0      0
         0      0      0      0      0      0      0      0      0      0
         0      0      0      0      0      0
0 2      0      0      0      0      0      0      0      0      0      0
         0      0      1      1      1      1      1      0      0      0
         0      0      0      0      0      0      0      0      0      0
         0      0      0      0      0      0
0 3      0      0      0      0      0      0      0      0      0      0
         0      1      1      1      1      1      1      1      1      1
         0      0      0      0      0      0      0      0      0      0
         0      0      0      0      0      0
0 4      0      0      0      0      0      0      0      0      0      0
         1      1      1      1      1      1      1      1      1      1
         1      1      0      0      0      0      0      0      0      0
         0      0      0      0      0      0
0 5      0      0      0      0      0      0      0      0      0      1
```

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | | | | |
| 0 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | | | | |
| 0 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | | | | |
| 0 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | | | | |
| 0 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | | | | |
| 0 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | | | | |
| 0 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | | | | |
| 0 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | | | | |
| 0 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 0 | 0 | 0 | 0 | 0 | 0 | | | | |
| 0 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 0 | 0 | 0 | 0 | 0 | | | | |
| 0 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 0 | 0 | 0 | 0 | | | | |
| 0 16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 0 | 0 | 0 | 0 | | | | |
| 0 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 0 | 0 | 0 | | | | |
| 0 18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 0 | 0 | | | | |
| 0 19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 0 | 0 | | | | |
| 0 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 0 | | | | |
| 0 21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 0 | | | | |
| 0 22 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 0 | | | | |
| 0 23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 0 | | | | |
| 0 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 0 | | | | |
| 0 25 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

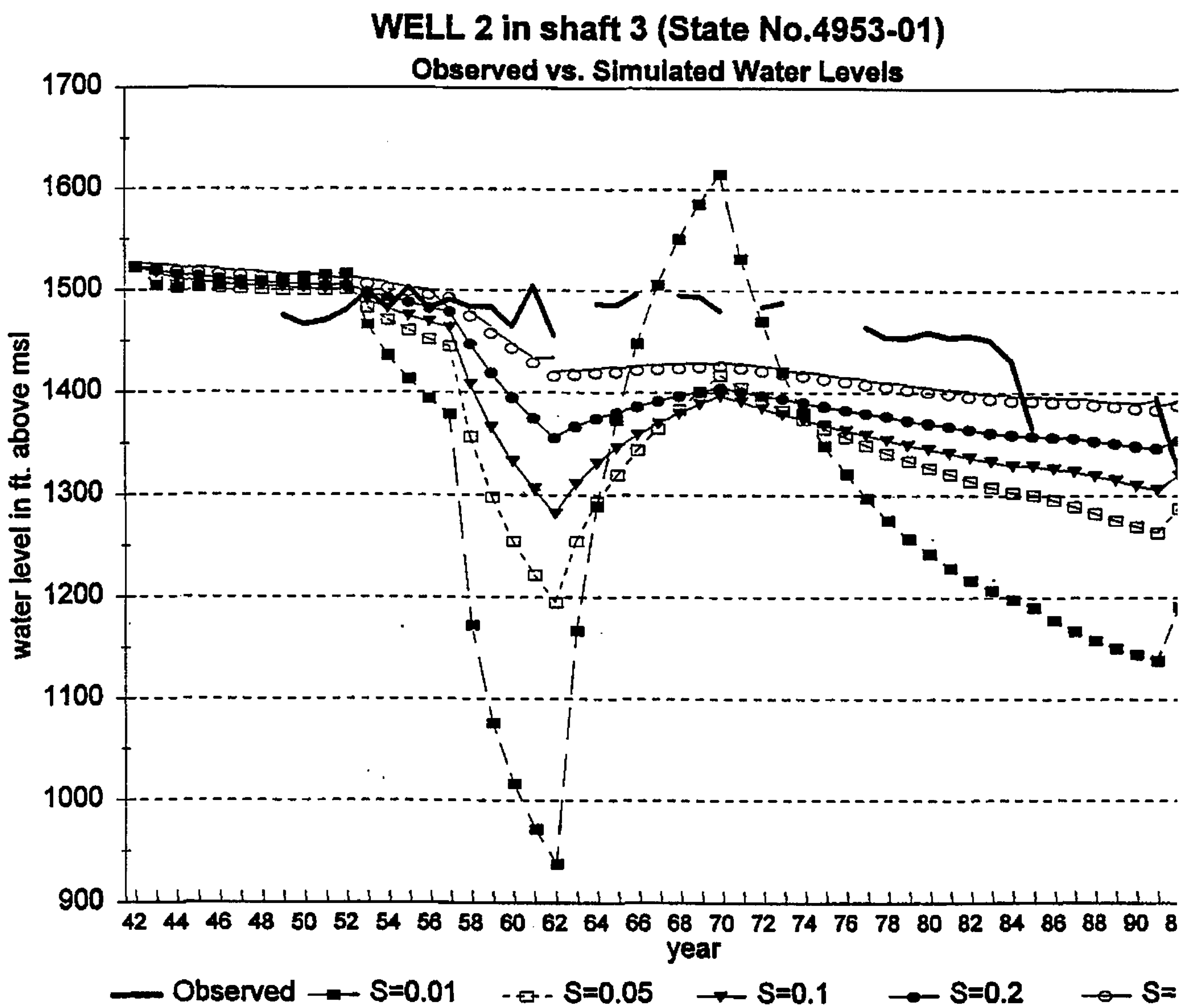

0.26
0.27
0.28
0.29
0.30
0.31
0.32
0.33
0.34
0.35
0.36
0.37
0.38
0.39
0.40
0.41
0.42
0.43
0.44
0.45

```
        1     1     1     1     0     0
0 46    0     0     0     0     0     0     0     0     0     0
        1     1     1     1     1     1     1     1     1     1
        1     1     1     1     1     1     1     1     1     1
        1     1     1     0     0     0
0 47    0     0     0     0     0     0     0     0     0     0
        0     0     0     0     1     1     1     1     1     1
        1     1     1     1     1     1     1     1     1     1
        1     1     0     0     0     0
0 48    0     0     0     0     0     0     0     0     0     0
        0     0     0     0     0     0     0     0     1     1
        1     1     1     1     1     1     1     1     1     1
        0     0     0     0     0     0
0 49    0     0     0     0     0     0     0     0     0     0
        0     0     0     0     0     0     0     0     0     1
        1     1     1     1     1     0     0     0     0     0
        0     0     0     0     0     0
0 50    0     0     0     0     0     0     0     0     0     0
        0     0     0     0     0     0     0     0     0     0
        0     0     0     0     0     0     0     0     0     0
        0     0     0     0     0     0
0AQUIFER HEAD WILL BE SET TO 0.00000    AT ALL NO-FLOW NODES (IBOUND=0).
0

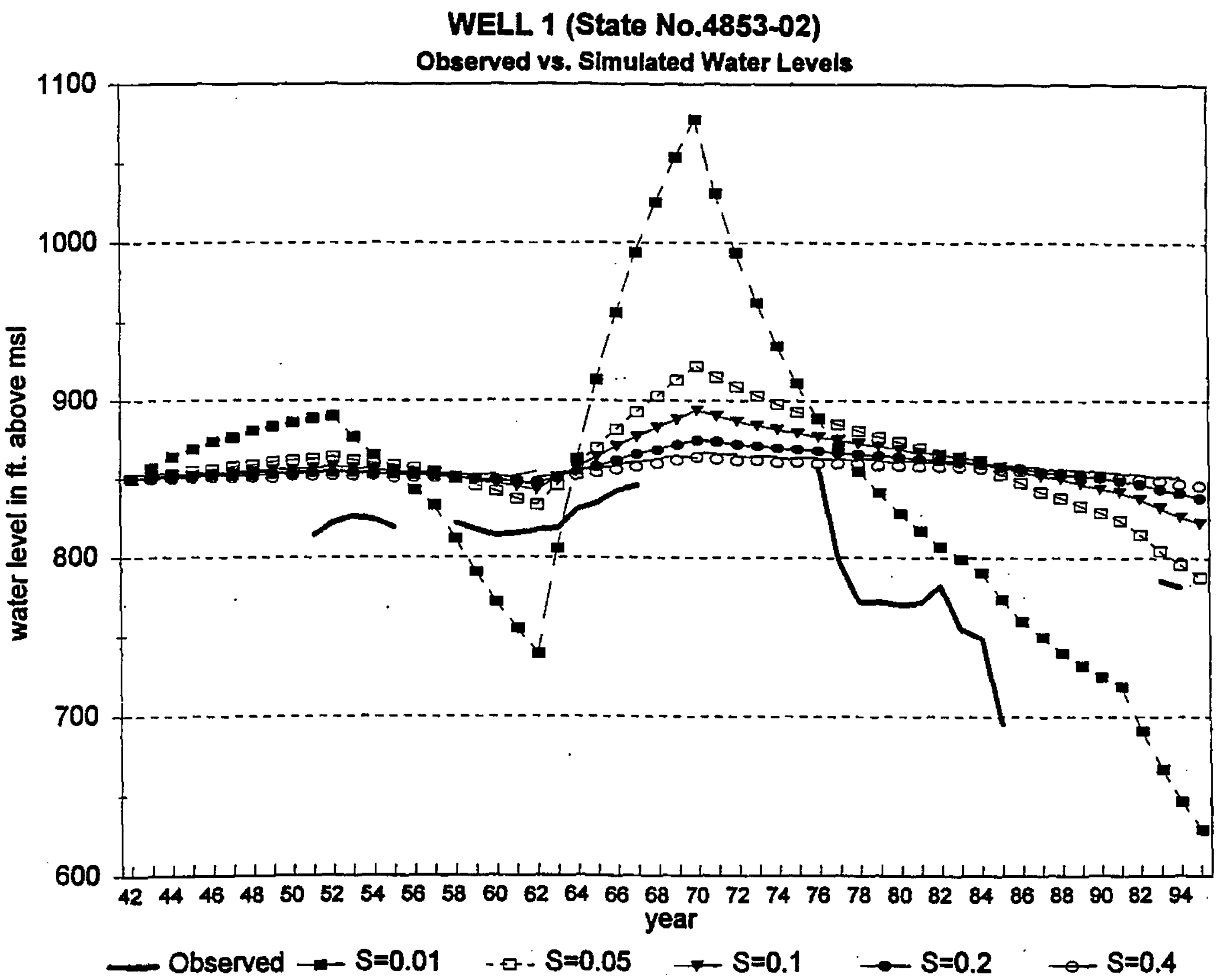

                 INITIAL HEAD, LAYER  1 WILL BE READ UNFORMATTED ON UNIT 35
                 ----------------------------------------------------------

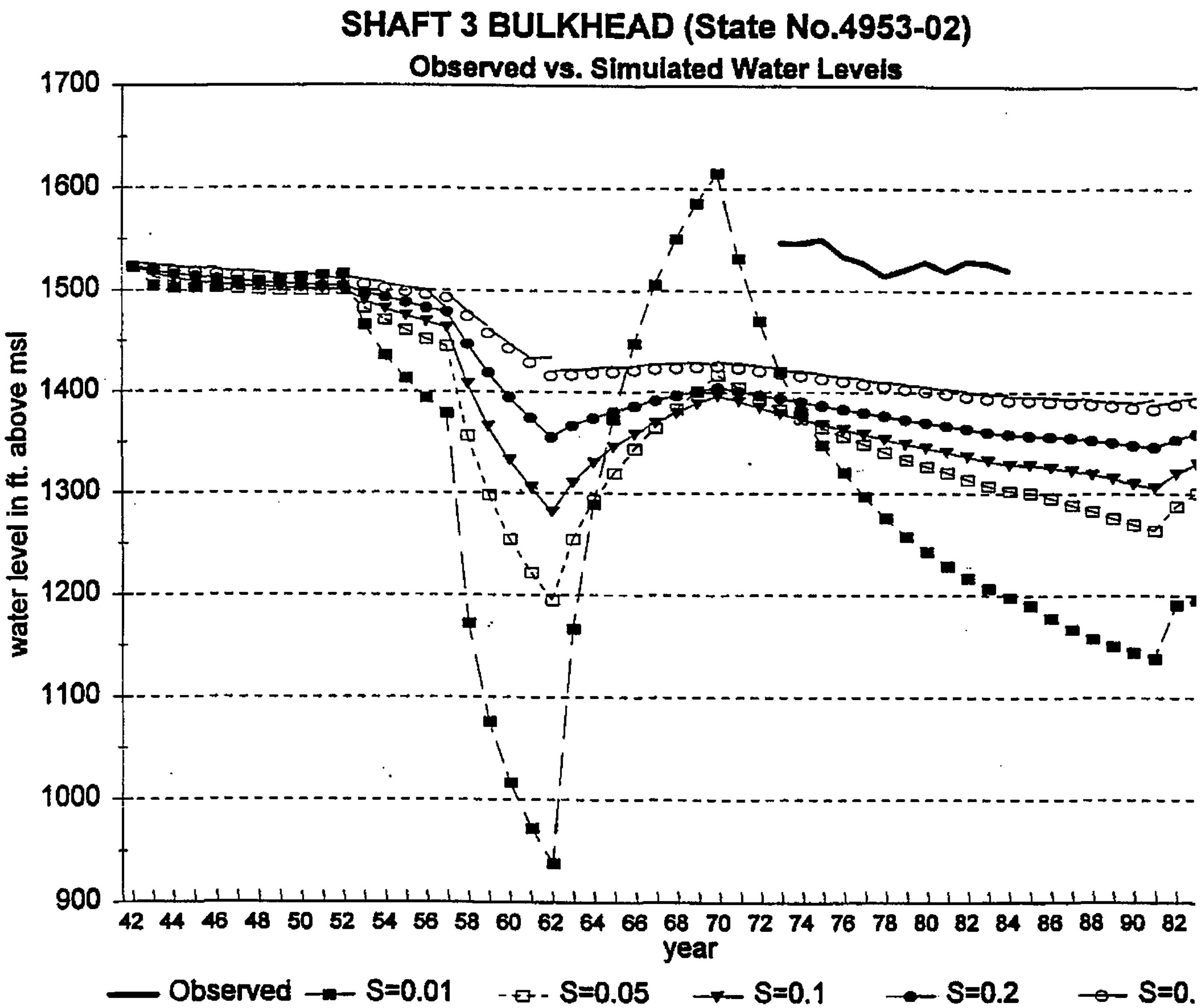
        1         2         3         4         5         6         7         8         9        10
       11        12        13        14        15        16        17        18        19        20
       21        22        23        24        25        26        27        28        29        30
       31        32        33        34        35        36
..............................................................................................
0 1  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 2  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    2.3181E-07 7.0106E-05 1.0295E-04 9.6275E-05 7.4483E-07 0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 3  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    3.4317E-07 1.6217E-04 7.0209E-02 0.1031    9.6448E-02 6.5004E-04 0.2544    0.3812    0.4357
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 4  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     3.3271E-07 1.8169E-04 9.2588E-02 0.1742    0.2313    0.2656    0.2916    0.4010    0.4871    0.5337
     0.5898    0.6046    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 5  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    2.1403E-07
     1.5168E-04 8.9400E-02 0.1907    0.2852    0.3623    0.4232    0.4789    0.5512    0.6142    0.6580
     0.6864    0.6796    0.6910    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 6  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    6.2760E-05
     6.2874E-02 0.1615    0.2766    0.3942    0.4892    0.5651    0.6304    0.6926    0.7445    0.7810
     0.8006    0.7969    0.7714    0.7732    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 7  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    8.9539E-05
     8.9719E-02 0.2062    0.3409    0.5058    0.6151    0.6987    0.7682    0.8276    0.8743    0.9056
     0.9204    0.9161    0.8930    0.8522    0.8435    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 8  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    1.5585E-05
     1.5523E-02 111.6     124.8     0.6526    0.7485    0.8300    0.8998    0.9583    1.003     1.031
      1.042     1.035     1.012    0.9720    0.9175    0.8997    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 9  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    1.8702E-05
     1.8729E-02 151.2     200.1     154.6     0.8785    0.9556    1.025     1.086     1.132     1.155
      1.162     1.152     1.128     1.089     1.035    0.9690    0.9430    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 10  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    1.3096E-05
     1.3107E-02 148.5     221.9     217.1     144.6     1.074     1.144     1.210     1.258     1.278
      1.280     1.268     1.243     1.202     1.148     1.082     1.009    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 11  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    8.5463E-06
     8.5586E-03 109.4     178.1     192.7     190.4     137.0     1.260     1.331     1.377     1.396
      1.394     1.379     1.353     1.313     1.258     1.167     1.094     1.058    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 12  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    1.1546E-07
     1.0715E-04 9.8929E-02 0.2101    0.2952    148.1     198.6     184.0     1.455     1.486     1.505
      1.505     1.487     1.460     1.420     1.366     1.300     1.219     1.128     1.085    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
```

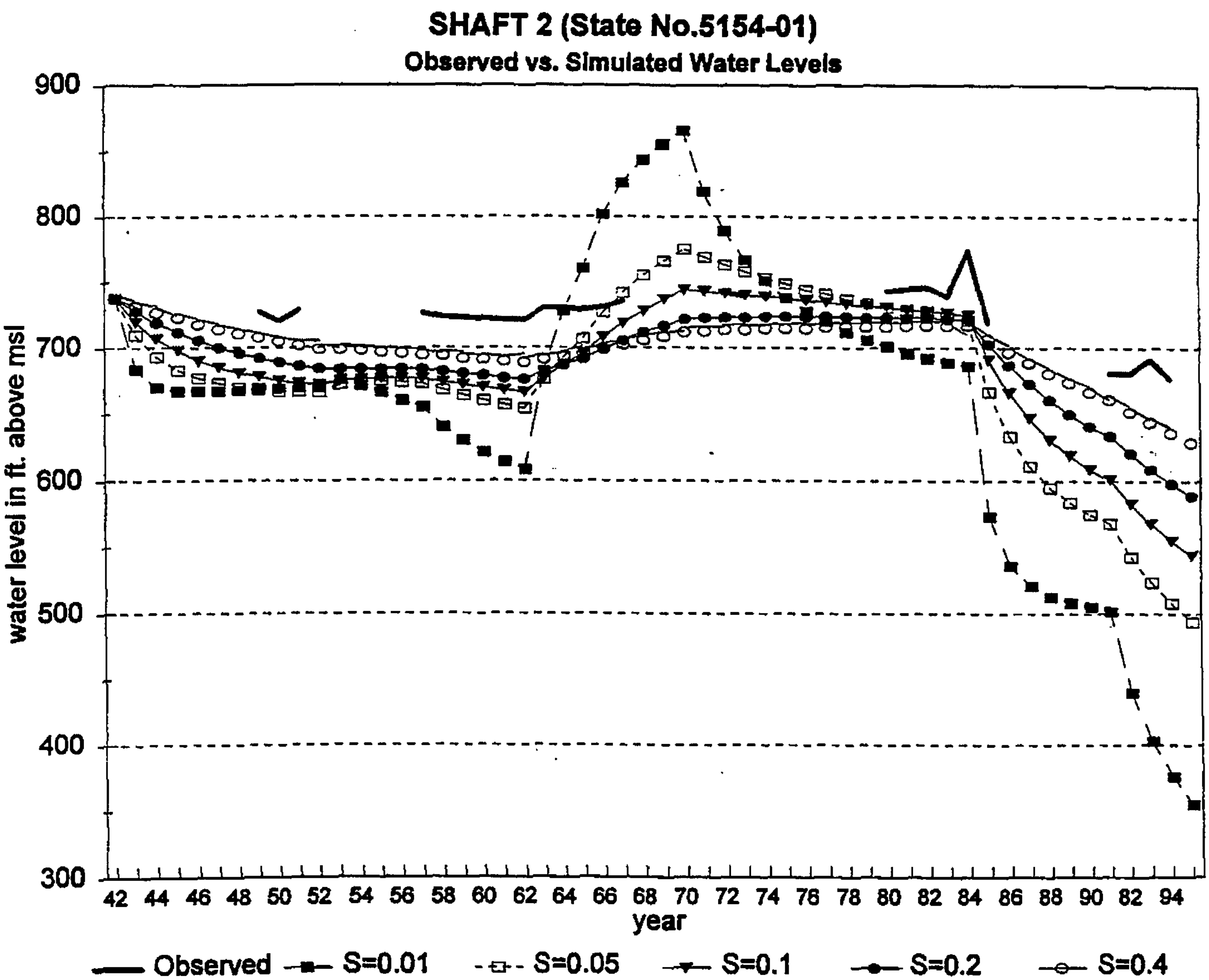
```
0 13  0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     7.3922E-05 7.4030E-02 0.1968     0.3156     0.4178     172.3      255.0      235.3      1.587      1.607
     1.609      1.589      1.561      1.522      1.471      1.410      1.336      1.250      1.150      1.102
     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
0 14  0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     3.2287E-07 2.4960E-04 0.1763     0.3289     0.4593     0.5778     224.3      324.6      217.3      1.718
     1.706      1.684      1.653      1.617      1.573      1.515      1.446      1.366      1.270      1.163
     1.110      0.0000     0.0000     0.0000     0.0000     0.0000
0 15  0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     0.0000     1.7151E-04 0.1716     0.3405     0.4903     0.6224     0.7455     325.7      268.6      1.793
     1.790      1.771      1.742      1.710      1.669      1.615      1.550      1.474      1.382      1.278
     1.167      1.111      0.0000     0.0000     0.0000     0.0000
0 16  0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     0.0000     1.7374E-04 0.1738     0.3497     0.5160     0.6509     0.7588     365.8      383.3      206.8
     1.850      1.854      1.834      1.801      1.762      1.710      1.647      1.571      1.481      1.380
     1.272      1.166      0.0000     0.0000     0.0000     0.0000
0 17  0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     0.0000     2.0458E-04 0.2047     0.3957     0.5479     0.6804     0.7863     394.5      440.1      309.9
     173.8      1.957      1.933      1.894      1.852      1.798      1.735      1.659      1.569      1.470
     1.356      1.222      1.151      0.0000     0.0000     0.0000
0 18  0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     0.0000     2.1822E-04 0.2182     0.4167     0.5755     0.7089     0.8153     412.5      472.5      369.3
     252.1      2.028      2.017      1.983      1.937      1.880      1.818      1.738      1.650      1.553
     1.442      1.319      1.191      1.121      0.0000     0.0000
0 19  0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     5.1780E-07 3.8427E-04 0.2507     0.4513     0.6095     0.7384     0.8398     419.6      491.5      417.7
     339.9      246.4      2.108      2.071      2.020      1.963      1.898      1.813      1.725      1.629
     1.522      1.402      1.278      1.162      0.0000     0.0000
0 20  0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     1.3457E-04 0.1347     0.3276     0.5060     0.6517     0.7681     0.8586     410.9      508.6      457.6
     378.6      287.7      2.191      2.152      2.104      2.044      1.973      1.890      1.799      1.702
     1.592      1.470      1.338      1.192      1.111      0.0000
0 21  0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
     2.1068E-04 0.2107     0.4069     0.5724     0.7030     0.8070     0.8864     394.6      509.2      488.0
     392.4      271.8      2.266      2.230      2.180      2.119      2.050      1.966      1.871      1.769
     1.654      1.529      1.393      1.257      1.139      0.0000
0 22  0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     6.7892E-07
     4.0927E-04 0.3008     0.4960     0.6490     0.7669     0.8595     0.9288     336.9      448.4      437.6
     376.0      270.7      2.337      2.297      2.253      2.190      2.120      2.037      1.941      1.834
     1.714      1.579      1.433      1.288      1.155      0.0000
0 23  0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     5.8845E-07 2.7101E-04
     0.1097     0.4914     0.6120     0.7366     0.8403     0.9210     0.9804     251.9      367.9      401.1
     380.1      290.2      2.391      2.354      2.311      2.257      2.195      2.116      2.019      1.905
     1.774      1.622      1.456      1.291      1.143      0.0000
0 24  0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     6.2931E-07 3.1862E-04 0.1623
     0.3281     0.5469     0.6979     0.8214     0.9223     1.000      1.054      231.4      356.3      416.9
     430.2      389.6      270.7      2.398      2.368      2.329      2.279      2.209      2.113      1.989
     1.840      1.661      1.463      1.261      1.064      0.0000
0 25  0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     6.5451E-07 3.1195E-04 0.1575     0.3184
     0.4802     0.6471     0.7888     0.9101     1.011      1.091      1.148      259.2      395.2      475.3
     511.2      505.6      434.1      267.1      2.429      2.412      2.383      2.327      2.235      2.095
     1.918      1.703      1.454      1.187      0.9469     0.0000
0 26  0.0000     0.0000     0.0000     0.0000     2.2019E-07 1.1040E-04 3.4387E-04 0.1556     0.3066     0.4581
     0.6059     0.7524     0.8845     1.001      1.104      1.190      1.255      321.1      469.7      560.2
     617.0      632.3      581.3      470.7      304.9      2.504      2.500      2.468      2.377      2.223
     2.017      1.759      1.447      1.068      0.6567     0.0000
0 27  0.0000     0.0000     0.0000     0.0000     1.1022E-04 0.1104     0.1892     0.3089     0.4390     0.5739
     0.7133     0.8501     0.9786     1.097      1.202      1.293      1.366      373.1      550.7      661.0
     738.0      755.3      721.4      646.7      531.6      364.8      2.644      2.658      2.558      2.378
     2.144      1.855      1.491      0.9680     2.4944E-03 0.0000
0 28  0.0000     0.0000     0.0000     3.2236E-07 1.6157E-04 0.2520     0.3291     0.4346     0.5518     0.6756
     0.8069     0.9405     1.070      1.192      1.303      1.400      1.481      415.4      616.5      760.5
     843.8      869.1      855.5      801.7      712.3      571.5      354.9      2.931      2.780      2.560
     2.302      2.011      1.673      1.273      0.8436     0.0000
0 29  0.0000     0.0000     0.0000     1.6143E-04 0.1619     0.3151     0.4244     0.5301     0.6442     0.7650
     0.8927     1.025      1.158      1.286      1.402      1.508      1.596      454.1      677.9      836.4
     932.9      978.5      991.0      948.2      843.6      656.9      374.0      3.265      3.039      2.767
     2.484      2.198      1.897      1.589      1.312      0.0000
0 30  0.0000     0.0000     2.5353E-10 2.1602E-07 0.3319     0.4116     0.5033     0.6018     0.7126     0.8339
     0.9643     1.101      1.241      1.376      1.500      1.612      1.710      506.9      741.7      895.0
     1001.      1079.      1131.      1116.      993.6      738.2      4.255      3.748      3.326      2.971
     2.658      2.378      2.108      1.843      1.608      0.0000
0 31  0.0000     0.0000     3.8021E-08 2.1960E-05 0.4195     0.4760     0.5552     0.6481     0.7580     0.8835
     1.020      1.166      1.320      1.464      1.596      1.714      1.824      586.6      808.1      953.8
     1078.      1191.      1273.      1287.      1155.      859.2      4.528      4.114      3.533      3.111
     2.786      2.531      2.283      2.042      1.820      0.0000
0 32  0.0000     0.0000     1.6175E-05 1.6197E-02 137.8      177.9      173.7      170.0      184.6      217.6
     262.8      346.1      476.5      529.1      549.6      566.2      608.3      749.4      871.6      1014.
     1154.      1287.      1392.      1408.      1240.      949.2      5.000      4.620      183.5      158.8
     2.821      2.652      2.431      2.201      1.980      0.0000
0 33  0.0000     0.0000     2.6065E-05 2.6122E-02 193.0      250.7      250.3      243.7      259.7      304.3
```



WELL 2 in shaft 3 (State No.4953-01)
Observed vs. Simulated Water Levels
1700
1600
1500
1400
1300
1200
1100
1000
900
water level in ft. above msl
42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90
year
Observed
S=0.01
S=0.05
S=0.1
S=0.2

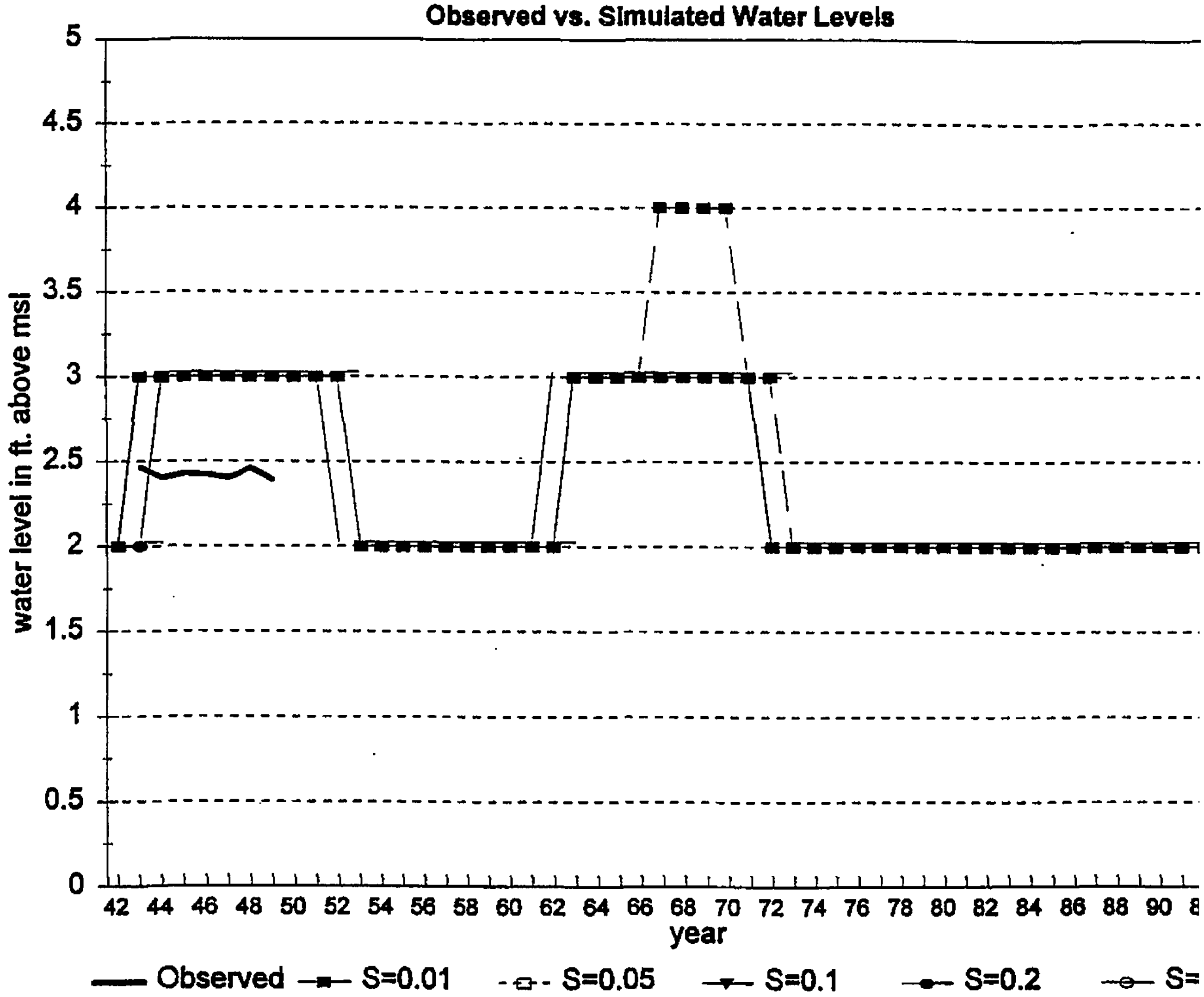

WELL 1 (State No.4853-02)
Observed vs. Simulated Water Levels
1100
1000
900
800
700
600
water level in ft. above msl
42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94
year
Observed
S=0.01
S=0.05
S=0.1
S=0.2
S=0.4


SHAFT 3 BULKHEAD (State No.4953-02)
Observed vs. Simulated Water Levels
1700
1600
1500
1400
1300
1200
1100
1000
900
water level in ft. above msl
42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 82
year
Observed
S=0.01
S=0.05
S=0.1
S=0.2
S=0.


SHAFT 2 (State No.5154-01)
Observed vs. Simulated Water Levels
900
800
700
600
500
400
300
water level in ft. above msl
42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 82 94
year
Observed
S=0.01
S=0.05
S=0.1
S=0.2
S=0.4

## SHAFT 1 (State No.5253-01)

### Observed vs. Simulated Water Levels



## APPENDIX F

## Appendix E-1. GIS Calculated Stress Period Recharge in cfd

| Month | Monthly Recharge, *R*, in million cfd | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Period 1 '42-'51 | Period 2 '52-'56 | Period 3 '57-'8/61 | Period 4 '9/62-'64 | Period 5 '65-'69 | Period 6 '70-'83 | Period 7 '84-'90 | Period 8 '91-'94 |
| Jan | 30.50 | 20.79 | 26.40 | 53.91 | 36.04 | 35.10 | 12.48 | 10.58 |
| Feb | 11.18 | 9.86 | 5.19 | 3.15 | 16.64 | 14.10 | 15.52 | 10.19 |
| Mar | 19.14 | 7.43 | 9.75 | 35.03 | 16.36 | 6.74 | 6.95 | 3.86 |
| Apr | 17.51 | 2.02 | 2.00 | 16.96 | 20.49 | 8.00 | 12.19 | 0.72 |
| May | 2.26 | 1.24 | 6.38 | 11.83 | 9.07 | 1.82 | 2.72 | 2.36 |
| Jun | 1.07 | 0.42 | 0.96 | 0.50 | 0.60 | 0.80 | 0.69 | 0.99 |
| Jul | 1.64 | 1.44 | 0.80 | 2.91 | 2.84 | 1.00 | 1.45 | 1.31 |
| Aug | 0.83 | 0.47 | 0.67 | 0.75 | 0.92 | 0.80 | 0.43 | 0.52 |
| Sep | 1.50 | 1.80 | 1.77 | 0.78 | 8.22 | 1.14 | 1.97 | 4.73 |
| Oct | 1.86 | 2.57 | 2.39 | 10.54 | 6.12 | 2.83 | 6.37 | 7.09 |
| Nov | 8.45 | 16.09 | 9.48 | 13.25 | 29.25 | 7.19 | 14.73 | 6.86 |
| Dec | 13.72 | 25.03 | 12.88 | 11.67 | 24.92 | 16.67 | 22.53 | 8.95 |
| Year | 9.17 | 7.44 | 6.56 | 13.44 | 14.29 | 8.02 | 8.17 | 4.86 |

## Appendix E-2. GIS Calculated Stress Period Recharge in mgd

| Month | Monthly Recharge, *R*, in mgd | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Period 1 '42-'51 | Period 2 '52-'56 | Period 3 '57-'8/61 | Period 4 '9/62-'64 | Period 5 '65-'69 | Period 6 '70-'83 | Period 7 '84-'90 | Period 8 '91-'94 |
| Jan | 228.02 | 155.41 | 197.42 | 403.04 | 269.44 | 262.46 | 93.31 | 79.11 |
| Feb | 83.60 | 73.73 | 38.79 | 23.54 | 124.43 | 105.43 | 116.03 | 76.31 |
| Mar | 143.11 | 55.52 | 72.90 | 261.94 | 122.31 | 50.36 | 51.98 | 28.87 |
| Apr | 130.92 | 15.14 | 14.96 | 126.85 | 153.20 | 59.83 | 91.18 | 5.39 |
| May | 16.93 | 9.27 | 47.73 | 88.47 | 67.78 | 13.59 | 20.36 | 17.63 |
| Jun | 8.01 | 3.16 | 4.16 | 3.76 | 4.50 | 6.00 | 5.19 | 7.41 |
| Jul | 12.23 | 10.80 | 5.99 | 21.77 | 21.21 | 7.45 | 10.82 | 9.82 |
| Aug | 6.21 | 4.29 | 5.02 | 5.62 | 6.92 | 5.96 | 3.20 | 4.67 |
| Sep | 11.20 | 13.48 | 13.27 | 5.84 | 61.48 | 8.49 | 14.71 | 35.39 |
| Oct | 13.88 | 19.18 | 17.86 | 78.83 | 45.74 | 21.18 | 47.60 | 53.01 |
| Nov | 63.20 | 120.31 | 70.91 | 99.08 | 218.69 | 53.78 | 110.11 | 51.32 |
| Dec | 102.59 | 187.15 | 96.33 | 87.29 | 186.29 | 124.67 | 168.42 | 66.90 |
| Year | 68.33 | 55.62 | 49.03 | 100.50 | 106.83 | 59.93 | 61.08 | 36.31 |

APPENDIX E

```
0          CUMULATIVE VOLUMES      L**3                    RATES FOR THIS TIME STEP      L**3/T

              IN:                                       IN:
              ---                                       ---
               STORAGE =  0.00000                          STORAGE =  0.00000
           CONSTANT HEAD =  0.00000                     CONSTANT HEAD =  0.00000
                 WELLS =  0.00000                          WELLS =  0.00000
                DRAINS =  0.00000                         DRAINS =  0.00000
              RECHARGE =  0.82316E+07                     RECHARGE =  0.82316E+07
           RIVER LEAKAGE =  0.00000                     RIVER LEAKAGE =  0.00000
0              TOTAL IN =  0.82316E+07                     TOTAL IN =  0.82316E+07
0             OUT:                                      OUT:
              ----                                      ----
               STORAGE =  0.00000                          STORAGE =  0.00000
           CONSTANT HEAD =  0.00000                     CONSTANT HEAD =  0.00000
                 WELLS =  0.00000                          WELLS =  0.00000
                DRAINS =   43538.                         DRAINS =   43538.
              RECHARGE =  0.00000                         RECHARGE =  0.00000
           RIVER LEAKAGE =  0.81884E+07                 RIVER LEAKAGE =  0.81884E+07
0             TOTAL OUT =  0.82320E+07                    TOTAL OUT =  0.82320E+07
0              IN - OUT =  -338.50                         IN - OUT =  -338.50
0       PERCENT DISCREPANCY =          0.00           PERCENT DISCREPANCY =          0.00

0

     TIME SUMMARY AT END OF TIME STEP  1 IN STRESS PERIOD  1
                    SECONDS     MINUTES      HOURS       DAYS        YEARS
                    -----------------------------------------------------------
  TIME STEP LENGTH   86400.0     1440.00     24.0000     1.00000   0.273785E-02
 STRESS PERIOD TIME  86400.0     1440.00     24.0000     1.00000   0.273785E-02
TOTAL SIMULATION TIME 86400.0    1440.00     24.0000     1.00000   0.273785E-02
1
```

```
      1154.     1287.     1392.     1406.     1240.     949.2     5.000     4.620     183.5     158.8
      2.821     2.652     2.431     2.201     1.980     0.0000
 0 33  0.0000    0.0000    2.6085E-05 2.6122E-02 193.0    250.7     250.3     243.7     259.7     304.3
      368.1     476.6     476.7     839.1     839.8     840.9     842.2     843.9     845.6     1048.
      1208.     1356.     1476.     1506.     1404.     1095.     5.578     334.8     269.4     192.9
      2.982     2.796     2.567     2.333     2.108     0.0000
 0 34  0.0000    0.0000    2.4067E-05 2.4061E-02 192.0    260.3     269.4     252.8     254.8     304.9
      375.9     476.6     476.8     628.5     758.9     759.1     759.2     843.7     847.0     1058.
      1251.     1421.     1531.     1601.     1539.     1319.     891.1     470.7     4.039     3.722
      3.273     2.960     2.687     2.434     2.198     0.0000
 0 35  0.0000    8.2306E-08 5.1283E-05 2.0184E-02 146.1    200.4     211.0     198.7     182.3     219.1
      302.7     476.5     476.8     628.2     758.8     759.0     759.2     759.4     848.2     1035.
      1280.     1523.     1523.     1667.     1641.     1453.     1047.     4.654     4.197     3.794
      3.398     3.059     2.768     2.500     2.257     0.0000
 0 36  0.0000    3.1187E-05 3.1279E-02 0.1249   0.2515    0.3928    0.5439    0.7039    0.8730    1.049
      1.244     1.478     627.3     627.9     758.6     758.8     759.1     759.3     849.2     850.1
      1256.     1492.     1625.     1743.     1729.     1562.     1172.     4.722     4.244     3.815
      3.433     3.096     2.798     2.528     2.281     0.0000
 0 37  0.0000    1.4431E-07 1.1341E-04 8.2574E-02 0.1994  0.3365    0.4882    0.6544    0.8315    0.9941
      1.157     273.9     551.0     757.7     758.2     758.6     759.0     759.4     927.7     1020.
      1284.     1504.     1680.     1805.     1804.     1674.     1390.     888.9     4.179     3.745
      3.392     3.073     2.780     2.512     2.266     0.0000
 0 38  0.0000    0.0000    3.0643E-07 1.9363E-04 0.1116  0.2463    0.3974    0.5724    0.7849    0.9207
      189.5     318.9     433.1     545.8     757.9     758.3     758.8     927.3     927.8     928.4
      1273.     1514.     1718.     1839.     1853.     1761.     1550.     1199.     705.8     3.566
      3.280     2.986     2.712     2.456     2.216     0.0000
 0 39  0.0000    0.0000    0.0000    4.3120E-07 2.3842E-04 0.1275  0.2633  0.4325    91.47     170.0
      242.9     273.0     235.6     1.882     6.649     6.831     926.1     927.1     927.8     928.4
      1276.     1515.     1723.     1841.     1868.     1807.     1629.     1328.     886.6     3.510
      3.151     2.868     2.609     2.366     2.136     0.0000
 0 40  0.0000    0.0000    0.0000    0.0000    4.5213E-07 2.1461E-04 8.7904E-02 8.6237E-02 0.1359  168.2
      215.2     174.2     1.601     1.751     6.317     6.667     683.8     854.7     928.0     1090.
      1311.     1514.     1696.     1810.     1845.     1803.     1643.     1374.     1015.     550.5
      2.928     2.701     2.465     2.241     2.032     0.0000
 0 41  0.0000    0.0000    0.0000    0.0000    0.0000    3.3019E-07 1.1625E-04 2.8796E-02 1.9698E-02 117.2
      131.9     1.140     1.381     4.846     5.625     342.5     666.8     849.6     981.6     1139.
      1320.     1491.     1647.     1751.     1781.     1744.     1595.     1352.     1063.     680.8
      2.821     2.523     2.291     2.082     1.910     0.0000
 0 42  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    1.4469E-07 2.8730E-05 1.9668E-05 1.4448E-02
      0.5255    0.8427    3.201     4.046     155.9     361.4     649.8     840.6     964.1     1139.
      1292.     1438.     1586.     1678.     1689.     1633.     1497.     1298.     1065.     774.9
      404.9     2.268     2.076     1.867     1.800     0.0000
 0 43  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    2.0954E-07 1.9029E-04
      0.1766    1.444     2.335     49.31     0.8886    1.054     536.5     768.8     932.2     1083.
      1222.     1349.     1458.     1524.     1523.     1471.     1361.     1204.     1012.     779.0
      486.4     2.127     1.859     1.677     0.0000    0.0000
 0 44  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    9.0002E-07
      7.1153E-04 0.5372   0.1318    0.4470    0.6783    0.3055    430.8     646.9     811.6     967.8
      1107.     1216.     1298.     1341.     1331.     1280.     1187.     1055.     898.7     699.2
      483.2     234.1     1.539     1.458     0.0000    0.0000
 0 45  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      1.6574E-04 0.1655   0.1241    0.1932    7.7318E-03 0.2175   287.1     448.1     590.3     783.1
      942.6     1043.     1108.     1133.     1108.     1047.     964.0     850.1     706.8     510.0
      350.4     197.1     1.252     1.292     0.0000    0.0000
 0 46  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      3.3023E-07 1.6515E-04 1.2414E-04 1.9288E-04 7.7628E-05 6.9625E-02 5.7704E-02 7.8608E-02 0.1980  481.8
      706.6     816.8     869.9     877.2     825.6     716.8     641.0     550.0     405.7     0.9490
      0.8482    0.8729    1.012     0.0000    0.0000    0.0000
 0 47  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      0.0000    0.0000    0.0000    0.0000    1.4699E-07 6.9674E-05 5.7683E-05 7.8703E-05 2.6685E-04 6.9527E-02
      386.7     512.7     555.5     546.5     448.8     0.7996    0.7984    0.7960    0.7782    0.7857
      0.7818    0.7880    0.0000    0.0000    0.0000    0.0000
 0 48  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    3.6433E-07 9.8213E-05
      2.9072E-02 9.3986E-02 0.1072  0.1052    0.3116    0.5746    0.6682    0.7002    0.7061    0.7105
      0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
 0 49  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    1.2704E-07
      2.9080E-05 9.3852E-05 1.0706E-04 1.0532E-04 3.1116E-04 0.0000 0.0000  0.0000    0.0000    0.0000
      0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
 0 50  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0HEAD WILL BE SAVED ON UNIT 30 AT END OF TIME STEP  1, STRESS PERIOD  1
0DRAWDOWN WILL BE SAVED ON UNIT 40 AT END OF TIME STEP  1, STRESS PERIOD  1
0

                    VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP  1 IN STRESS PERIOD  1
                    ------------------------------------------------------------------------------
```

```
      1.0715E-04 9.8929E-02 0.2101    0.2952    148.1     198.6     184.0     1.455     1.486     1.505
       1.505     1.487     1.460     1.420     1.366     1.300     1.219     1.128     1.065     0.0000
      0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 13  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      7.3922E-05 7.4030E-02 0.1966    0.3156    0.4178    172.3     255.0     235.3     1.587     1.607
       1.609     1.589     1.561     1.522     1.471     1.410     1.336     1.250     1.150     1.102
      0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 14  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      3.2287E-07 2.4960E-04 0.1763    0.3289    0.4593    0.5778    224.3     324.6     217.3     1.718
       1.706     1.684     1.653     1.617     1.573     1.515     1.446     1.366     1.270     1.183
       1.110    0.0000    0.0000    0.0000    0.0000    0.0000
0 15  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      0.0000    1.7151E-04 0.1716   0.3405    0.4903    0.6224    0.7456    325.7     268.6     1.793
       1.790     1.771     1.742     1.710     1.669     1.615     1.550     1.474     1.382     1.278
       1.167     1.111    0.0000    0.0000    0.0000    0.0000
0 16  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      0.0000    1.7374E-04 0.1738   0.3497    0.5160    0.6509    0.7588    365.8     383.3     206.6
       1.850     1.854     1.834     1.801     1.762     1.710     1.647     1.571     1.481     1.380
       1.272     1.166    0.0000    0.0000    0.0000    0.0000
0 17  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      0.0000    2.0458E-04 0.2047   0.3957    0.5479    0.6804    0.7863    394.5     440.1     309.9
       173.8     1.957     1.933     1.894     1.852     1.798     1.735     1.659     1.569     1.470
       1.356     1.222     1.151    0.0000    0.0000    0.0000
0 18  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      0.0000    2.1822E-04 0.2162   0.4157    0.5755    0.7069    0.8153    412.5     472.5     369.3
       252.1     2.026     2.017     1.983     1.937     1.880     1.818     1.738     1.650     1.553
       1.442     1.319     1.191     1.121    0.0000    0.0000
0 19  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      5.1780E-07 3.8427E-04 0.2507    0.4513    0.6095    0.7384    0.8398    419.6     491.5     417.7
       339.9     246.4     2.108     2.071     2.020     1.963     1.896     1.813     1.725     1.629
       1.522     1.402     1.278     1.162    0.0000    0.0000
0 20  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      1.3457E-04 0.1347    0.3276    0.5060    0.6517    0.7681    0.8566    410.9     508.6     457.6
       376.8     287.7     2.191     2.152     2.104     2.044     1.973     1.890     1.799     1.702
       1.592     1.470     1.338     1.192     1.111    0.0000
0 21  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
      2.1066E-04 0.2107    0.4069    0.5724    0.7030    0.8070    0.8864    394.6     509.2     488.0
       392.4     271.8     2.266     2.230     2.180     2.119     2.050     1.966     1.871     1.769
       1.654     1.529     1.393     1.257     1.139    0.0000
0 22  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    6.7892E-07
      4.0927E-04 0.3006    0.4980    0.6490    0.7669    0.8596    0.9268    336.9     448.4     437.6
       376.0     270.7     2.337     2.297     2.253     2.190     2.120     2.037     1.941     1.834
       1.714     1.579     1.433     1.288     1.155    0.0000
0 23  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    5.8845E-07 2.7101E-04
      0.1097    0.4914    0.6120    0.7366    0.8403    0.9210    0.9804    251.9     367.9     401.1
       380.1     290.2     2.391     2.354     2.311     2.257     2.195     2.116     2.019     1.905
       1.774     1.622     1.456     1.291     1.143    0.0000
0 24  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    6.2931E-07 3.1862E-04 0.1623
      0.3281    0.5469    0.6979    0.8214    0.9223    1.000     1.054     231.4     356.3     416.9
       430.2     389.6     270.7     2.398     2.368     2.329     2.279     2.209     2.113     1.989
       1.840     1.661     1.463     1.261     1.064    0.0000
0 25  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    6.5451E-07 3.1195E-04 0.1575    0.3184
      0.4802    0.6471    0.7888    0.9101    1.011     1.091     1.148     259.2     395.2     475.3
       511.2     505.6     434.1     267.1     2.429     2.412     2.383     2.327     2.235     2.095
       1.918     1.703     1.454     1.187     0.9489    0.0000
0 26  0.0000    0.0000    0.0000    0.0000    2.2019E-07 1.1040E-04 3.4387E-04 0.1556    0.3066    0.4561
      0.6059    0.7524    0.8846    1.001     1.104     1.190     1.255     321.1     469.7     560.2
       617.0     632.3     581.3     470.7     304.9     2.504     2.500     2.468     2.377     2.223
       2.017     1.759     1.447     1.068     0.6567    0.0000
0 27  0.0000    0.0000    0.0000    0.0000    1.1022E-04 0.1104    0.1892    0.3089    0.4390    0.5739
      0.7133    0.8501    0.9786    1.097     1.202     1.293     1.366     373.1     550.7     661.0
       738.0     755.3     721.4     646.7     531.6     364.8     2.644     2.658     2.558     2.378
       2.144     1.855     1.491     0.9660    2.4944E-03 0.0000
0 28  0.0000    0.0000    0.0000    3.2236E-07 1.6157E-04 0.2520    0.3291    0.4346    0.5518    0.6756
      0.8069    0.9405    1.070     1.192     1.303     1.400     1.481     415.4     616.5     760.5
       843.8     869.1     855.5     801.7     712.3     571.5     354.9     2.931     2.780     2.560
       2.302     2.011     1.673     1.273     0.8436    0.0000
0 29  0.0000    0.0000    0.0000    1.6143E-04 0.1619    0.3151    0.4244    0.5301    0.6442    0.7650
      0.8927    1.025     1.158     1.285     1.402     1.506     1.595     454.1     677.9     836.4
       932.9     978.5     991.0     948.2     843.8     656.9     374.0     3.265     3.039     2.767
       2.484     2.196     1.897     1.589     1.312     0.0000
0 30  0.0000    0.0000    2.5353E-10 2.1602E-07 0.3319    0.4116    0.5033    0.6018    0.7126    0.8339
      0.9643    1.101     1.241     1.378     1.500     1.612     1.710     506.9     741.7     895.0
       1001.     1079.     1131.     1116.     993.6     738.2     4.255     3.748     3.326     2.971
       2.658     2.378     2.106     1.843     1.608     0.0000
0 31  0.0000    0.0000    3.8021E-06 2.1960E-05 0.4195    0.4760    0.5552    0.6481    0.7580    0.8835
       1.020     1.166     1.320     1.464     1.596     1.714     1.824     586.6     808.1     953.6
       1078.     1191.     1273.     1287.     1155.     859.2     4.528     4.114     3.533     3.111
       2.786     2.531     2.283     2.042     1.820     0.0000
0 32  0.0000    0.0000    1.6175E-05 1.6197E-02 137.8     177.9     173.7     170.0     184.6     217.6
       262.8     346.1     476.5     529.1     549.6     566.2     608.3     749.4     871.6     1014.
```

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0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 137  LAYER 1  ROW 23  COL 10  RATE -108402.3
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 138  LAYER 1  ROW 22  COL 10  RATE -271.5677
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 139  LAYER 1  ROW 22  COL 11  RATE -163708.5
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 140  LAYER 1  ROW 19  COL 11  RATE -207.1189
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 141  LAYER 1  ROW 20  COL 11  RATE -53826.54
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 142  LAYER 1  ROW 21  COL 11  RATE -84271.70
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 143  LAYER 1  ROW 14  COL 12  RATE -99636.40
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 144  LAYER 1  ROW 15  COL 12  RATE -68604.00
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 145  LAYER 1  ROW 16  COL 12  RATE -69496.23
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 146  LAYER 1  ROW 17  COL 12  RATE -81830.05
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 147  LAYER 1  ROW 18  COL 12  RATE -87288.31
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 148  LAYER 1  ROW 19  COL 12  RATE -153706.6
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 149  LAYER 1  ROW 12  COL 11  RATE -42858.30
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 150  LAYER 1  ROW 13  COL 11  RATE -29568.88
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 151  LAYER 1  ROW 14  COL 11  RATE -129.1490
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 152  LAYER 1  ROW  5  COL 10  RATE -85.61361
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 153  LAYER 1  ROW  6  COL 10  RATE -25111.96
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 154  LAYER 1  ROW  7  COL 10  RATE -35815.64
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 155  LAYER 1  ROW  8  COL 10  RATE -6233.916
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 156  LAYER 1  ROW  9  COL 10  RATE -7480.935
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 157  LAYER 1  ROW 10  COL 10  RATE -5238.204
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 158  LAYER 1  ROW 11  COL 10  RATE -3418.512
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 159  LAYER 1  ROW 12  COL 10  RATE -46.18445
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 160  LAYER 1  ROW  4  COL 11  RATE -133.0842
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 161  LAYER 1  ROW  5  COL 11  RATE -60672.87
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 162  LAYER 1  ROW  3  COL 12  RATE -137.2694
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 163  LAYER 1  ROW  4  COL 12  RATE -72677.49
0  RIVER LEAKAGE   PERIOD 1  STEP 1  REACH 164  LAYER 1  ROW  3  COL 13  RATE -64866.45
1            HEAD IN LAYER  1 AT END OF TIME STEP  1 IN STRESS PERIOD  1
         ---------------------------------------------------------

        1        2        3        4        5        6        7        8        9       10
       11       12       13       14       15       16       17       18       19       20
       21       22       23       24       25       26       27       28       29       30
       31       32       33       34       35       36
 ..........................................................................................
0 1  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 2  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    2.3181E-07 7.0106E-05 1.0295E-04 9.6275E-05 7.4483E-07 0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 3  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    3.4317E-07 1.6217E-04 7.0209E-02 0.1031    9.6446E-02 6.5004E-04 0.2544    0.3812    0.4357
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 4  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     3.3271E-07 1.8169E-04 9.2588E-02 0.1742   0.2313    0.2656    0.2916    0.4010    0.4871    0.5337
     0.5898    0.6046    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 5  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    2.1403E-07
     1.5168E-04 8.9400E-02 0.1907   0.2852    0.3623    0.4232    0.4789    0.5512    0.6142    0.6580
     0.6864    0.6796    0.6910    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 6  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    6.2780E-05
     6.2874E-02 0.1615   0.2756    0.3942    0.4892    0.5651    0.6304    0.6928    0.7445    0.7810
     0.8006    0.7969    0.7714    0.7732    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 7  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    8.9539E-05
     8.9719E-02 0.2062   0.3409    0.5058    0.6151    0.6987    0.7682    0.8278    0.8743    0.9056
     0.9204    0.9161    0.8930    0.8522    0.8436    0.0000    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 8  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    1.5585E-05
     1.5523E-02  111.8     124.8    0.6528    0.7485    0.8300    0.8996    0.9583    1.003     1.031
      1.042-     1.035     1.012    0.9720    0.9175    0.8997    0.0000    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 9  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    1.8702E-05
     1.8729E-02  151.2     200.1     154.6    0.8785    0.9565    1.025     1.066     1.132     1.155
      1.162      1.152     1.128     1.089     1.035    0.9690    0.9430    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 10  0.0000   0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    1.3096E-05
     1.3107E-02  148.5     221.9     217.1     144.6     1.074     1.144     1.210     1.258     1.278
      1.280      1.268     1.243     1.202     1.148     1.082     1.009    0.0000    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 11  0.0000   0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    8.5463E-06
     8.5586E-03  109.4     178.1     192.7     190.4     137.0     1.260     1.331     1.377     1.396
      1.394      1.379     1.353     1.313     1.258     1.187     1.094     1.058    0.0000    0.0000
     0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0 12  0.0000   0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    1.1546E-07
```

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 56 | LAYER 1 | ROW 35 | COL 35 | RATE -90268.85 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 57 | LAYER 1 | ROW 36 | COL 35 | RATE -91220.87 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 58 | LAYER 1 | ROW 37 | COL 35 | RATE -90626.80 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 59 | LAYER 1 | ROW 38 | COL 35 | RATE -88657.13 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 60 | LAYER 1 | ROW 39 | COL 35 | RATE -85458.96 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 61 | LAYER 1 | ROW 40 | COL 35 | RATE -81297.95 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 62 | LAYER 1 | ROW 41 | COL 35 | RATE -76412.17 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 63 | LAYER 1 | ROW 42 | COL 35 | RATE -72014.78 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 64 | LAYER 1 | ROW 42 | COL 34 | RATE -74666.69 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 65 | LAYER 1 | ROW 43 | COL 34 | RATE -67074.10 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 66 | LAYER 1 | ROW 44 | COL 34 | RATE -58312.19 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 67 | LAYER 1 | ROW 45 | COL 34 | RATE -51680.56 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 68 | LAYER 1 | ROW 45 | COL 33 | RATE -50084.20 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 69 | LAYER 1 | ROW 46 | COL 33 | RATE -40489.55 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 70 | LAYER 1 | ROW 46 | COL 32 | RATE -34916.14 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 71 | LAYER 1 | ROW 47 | COL 32 | RATE -31521.41 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 72 | LAYER 1 | ROW 47 | COL 30 | RATE -31428.78 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 73 | LAYER 1 | ROW 47 | COL 31 | RATE -31272.26 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 74 | LAYER 1 | ROW 48 | COL 25 | RATE -12462.38 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 75 | LAYER 1 | ROW 48 | COL 26 | RATE -22985.18 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 76 | LAYER 1 | ROW 48 | COL 27 | RATE -26727.04 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 77 | LAYER 1 | ROW 48 | COL 28 | RATE -28008.04 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 78 | LAYER 1 | ROW 48 | COL 29 | RATE -28245.12 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 79 | LAYER 1 | ROW 48 | COL 30 | RATE -28418.68 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 80 | LAYER 1 | ROW 49 | COL 20 | RATE -50.81551 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 81 | LAYER 1 | ROW 49 | COL 21 | RATE -11631.64 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 82 | LAYER 1 | ROW 49 | COL 22 | RATE -37540.80 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 83 | LAYER 1 | ROW 49 | COL 23 | RATE -42825.92 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 84 | LAYER 1 | ROW 49 | COL 24 | RATE -42128.72 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 85 | LAYER 1 | ROW 49 | COL 25 | RATE -124465.5 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 86 | LAYER 1 | ROW 48 | COL 19 | RATE -145.7339 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 87 | LAYER 1 | ROW 48 | COL 20 | RATE -39285.30 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 88 | LAYER 1 | ROW 47 | COL 15 | RATE -58.79745 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 89 | LAYER 1 | ROW 47 | COL 16 | RATE -27869.59 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 90 | LAYER 1 | ROW 47 | COL 17 | RATE -23073.21 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 91 | LAYER 1 | ROW 47 | COL 18 | RATE -31481.04 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 92 | LAYER 1 | ROW 47 | COL 19 | RATE -106740.0 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 93 | LAYER 1 | ROW 46 | COL 11 | RATE -132.0827 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 94 | LAYER 1 | ROW 46 | COL 12 | RATE -66061.30 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 95 | LAYER 1 | ROW 46 | COL 13 | RATE -49656.57 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 96 | LAYER 1 | ROW 46 | COL 14 | RATE -77153.77 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 97 | LAYER 1 | ROW 46 | COL 15 | RATE -31051.32 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 98 | LAYER 1 | ROW 44 | COL 11 | RATE -284612.6 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 99 | LAYER 1 | ROW 45 | COL 11 | RATE -86296.58 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 100 | LAYER 1 | ROW 44 | COL 10 | RATE -360.0085 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 101 | LAYER 1 | ROW 43 | COL 10 | RATE -76115.72 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 102 | LAYER 1 | ROW 43 | COL 9 | RATE -83.81532 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 103 | LAYER 1 | ROW 42 | COL 9 | RATE -7867.219 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 104 | LAYER 1 | ROW 42 | COL 7 | RATE -57.87478 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 105 | LAYER 1 | ROW 42 | COL 8 | RATE -11492.12 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 106 | LAYER 1 | ROW 41 | COL 7 | RATE -46498.40 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 107 | LAYER 1 | ROW 41 | COL 6 | RATE -132.0778 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 108 | LAYER 1 | ROW 40 | COL 5 | RATE -160.8516 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 109 | LAYER 1 | ROW 40 | COL 6 | RATE -85843.08 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 110 | LAYER 1 | ROW 39 | COL 4 | RATE -172.4791 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 111 | LAYER 1 | ROW 39 | COL 5 | RATE -95369.48 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 112 | LAYER 1 | ROW 38 | COL 3 | RATE -122.5735 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 113 | LAYER 1 | ROW 38 | COL 4 | RATE -77453.72 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 114 | LAYER 1 | ROW 37 | COL 2 | RATE -57.72408 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 115 | LAYER 1 | ROW 37 | COL 3 | RATE -45364.21 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 116 | LAYER 1 | ROW 35 | COL 2 | RATE -32.92231 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 117 | LAYER 1 | ROW 36 | COL 2 | RATE -12474.78 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 118 | LAYER 1 | ROW 35 | COL 3 | RATE -20513.37 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 119 | LAYER 1 | ROW 30 | COL 3 | RATE -0.1014119 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 120 | LAYER 1 | ROW 31 | COL 3 | RATE -15.20828 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 121 | LAYER 1 | ROW 32 | COL 3 | RATE -6469.845 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 122 | LAYER 1 | ROW 33 | COL 3 | RATE -10433.90 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 123 | LAYER 1 | ROW 34 | COL 3 | RATE -9626.815 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 124 | LAYER 1 | ROW 30 | COL 4 | RATE -86.40839 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 125 | LAYER 1 | ROW 28 | COL 4 | RATE -128.9424 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 126 | LAYER 1 | ROW 29 | COL 4 | RATE -64573.14 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 127 | LAYER 1 | ROW 26 | COL 5 | RATE -88.07444 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 128 | LAYER 1 | ROW 27 | COL 5 | RATE -44068.94 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 129 | LAYER 1 | ROW 28 | COL 5 | RATE -64627.06 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 130 | LAYER 1 | ROW 26 | COL 6 | RATE -44161.64 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 131 | LAYER 1 | ROW 26 | COL 7 | RATE -137548.5 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 132 | LAYER 1 | ROW 25 | COL 7 | RATE -261.8047 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 133 | LAYER 1 | ROW 25 | COL 8 | RATE -124779.8 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 134 | LAYER 1 | ROW 24 | COL 8 | RATE -251.7229 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 135 | LAYER 1 | ROW 24 | COL 9 | RATE -127446.4 |
| 0 | RIVER LEAKAGE | PERIOD 1 | STEP 1 | REACH 136 | LAYER 1 | ROW 23 | COL 9 | RATE -235.3760 |

```
          1     5    11  0.0000     0.4000E+09     -10.00       161
          1     3    12  0.0000     0.4000E+09     -10.00       162
          1     4    12  0.0000     0.4000E+09     -10.00       163
          1     3    13  0.0000     0.4000E+09     -10.00       164
0AVERAGE SEED = 0.00078879
 MINIMUM SEED = 0.00000019
0
   5 ITERATION PARAMETERS CALCULATED FROM AVERAGE SEED:

       0.0000000E+00  0.8324129E+00  0.9719146E+00  0.9952933E+00  0.9992112E+00
0
    1 ITERATIONS FOR TIME STEP   1 IN STRESS PERIOD  1
0MAXIMUM HEAD CHANGE FOR EACH ITERATION:
0 HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL HEAD CHANGE LAYER,ROW,COL HEAD CHANGE
LAYER,ROW,COL
 ------------------------------------------------------------------------------------------------
  0.6505E-03 (  1, 36, 20)
0
0HEAD/DRAWDOWN PRINTOUT FLAG = 1    TOTAL BUDGET PRINTOUT FLAG = 0    CELL-BY-CELL FLOW TERM FLAG = 1
0OUTPUT FLAGS FOR ALL LAYERS ARE THE SAME:
  HEAD   DRAWDOWN  HEAD  DRAWDOWN
 PRINTOUT  PRINTOUT  SAVE   SAVE
 ---------------------------------
    1      0     1     1
0        DRAINS  PERIOD  1  STEP  1  DRAIN  1  LAYER  1  ROW 32  COL  25  RATE  -34925.88
0        DRAINS  PERIOD  1  STEP  1  DRAIN  3  LAYER  1  ROW 33  COL  24  RATE  -8611.835
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH   1   LAYER  1   ROW   2   COL  13   RATE  -92.72423
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH   2   LAYER  1   ROW   2   COL  14   RATE  -28043.22
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH   3   LAYER  1   ROW   2   COL  15   RATE  -41180.27
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH   4   LAYER  1   ROW   2   COL  16   RATE  -38509.82
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH   5   LAYER  1   ROW   2   COL  17   RATE  -297.9317
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH   6   LAYER  1   ROW   3   COL  17   RATE  -260017.6
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH   7   LAYER  1   ROW   3   COL  18   RATE  -10177.65
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH   8   LAYER  1   ROW   3   COL  19   RATE  -15249.96
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH   9   LAYER  1   ROW   3   COL  20   RATE  -17428.94
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  10   LAYER  1   ROW   4   COL  20   RATE  -21346.47
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  11   LAYER  1   ROW   4   COL  21   RATE  -23593.95
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  12   LAYER  1   ROW   4   COL  22   RATE  -24182.16
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  13   LAYER  1   ROW   5   COL  22   RATE  -27184.64
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  14   LAYER  1   ROW   5   COL  23   RATE  -27640.89
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  15   LAYER  1   ROW   6   COL  23   RATE  -30856.13
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  16   LAYER  1   ROW   6   COL  24   RATE  -30929.57
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  17   LAYER  1   ROW   7   COL  24   RATE  -34086.05
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  18   LAYER  1   ROW   7   COL  25   RATE  -33741.84
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  19   LAYER  1   ROW   8   COL  25   RATE  -36700.64
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  20   LAYER  1   ROW   8   COL  26   RATE  -35988.05
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  21   LAYER  1   ROW   9   COL  26   RATE  -38758.43
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  22   LAYER  1   ROW   9   COL  27   RATE  -37718.82
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  23   LAYER  1   ROW  10   COL  27   RATE  -40347.24
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  24   LAYER  1   ROW  11   COL  27   RATE  -43758.41
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  25   LAYER  1   ROW  11   COL  28   RATE  -42331.44
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  26   LAYER  1   ROW  12   COL  28   RATE  -45103.38
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  27   LAYER  1   ROW  12   COL  29   RATE  -43397.85
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  28   LAYER  1   ROW  13   COL  29   RATE  -46008.22
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  29   LAYER  1   ROW  13   COL  30   RATE  -44089.35
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  30   LAYER  1   ROW  14   COL  30   RATE  -46537.84
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  31   LAYER  1   ROW  14   COL  31   RATE  -44395.05
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  32   LAYER  1   ROW  15   COL  31   RATE  -46668.24
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  33   LAYER  1   ROW  15   COL  32   RATE  -44451.42
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  34   LAYER  1   ROW  16   COL  32   RATE  -46638.89
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  35   LAYER  1   ROW  17   COL  32   RATE  -48871.62
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  36   LAYER  1   ROW  17   COL  33   RATE  -46029.78
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  37   LAYER  1   ROW  18   COL  33   RATE  -47648.09
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  38   LAYER  1   ROW  18   COL  34   RATE  -44849.06
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  39   LAYER  1   ROW  19   COL  34   RATE  -46470.16
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  40   LAYER  1   ROW  20   COL  34   RATE  -47863.44
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  41   LAYER  1   ROW  20   COL  35   RATE  -44439.71
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  42   LAYER  1   ROW  21   COL  35   RATE  -45541.65
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  43   LAYER  1   ROW  22   COL  35   RATE  -46206.64
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  44   LAYER  1   ROW  23   COL  35   RATE  -45728.28
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  45   LAYER  1   ROW  24   COL  35   RATE  -43350.37
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  46   LAYER  1   ROW  25   COL  35   RATE  -37966.51
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  47   LAYER  1   ROW  26   COL  35   RATE  -26269.85
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  48   LAYER  1   ROW  27   COL  35   RATE  -997777.6
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  49   LAYER  1   ROW  28   COL  35   RATE  -33742.77
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  50   LAYER  1   ROW  29   COL  35   RATE  -52499.19
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  51   LAYER  1   ROW  30   COL  35   RATE  -64330.21
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  52   LAYER  1   ROW  31   COL  35   RATE  -72783.05
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  53   LAYER  1   ROW  32   COL  35   RATE  -79207.48
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  54   LAYER  1   ROW  33   COL  35   RATE  -84240.19
0  RIVER LEAKAGE   PERIOD  1   STEP  1   REACH  55   LAYER  1   ROW  34   COL  35   RATE  -87911.41
```

| | | | | | | |
|---|---|---|---|---|---|---|
| 1 | 49 | 20 | 0.0000 | 0.4000E+09 | -10.00 | 80 |
| 1 | 49 | 21 | 0.0000 | 0.4000E+09 | -10.00 | 81 |
| 1 | 49 | 22 | 0.0000 | 0.4000E+09 | -10.00 | 82 |
| 1 | 49 | 23 | 0.0000 | 0.4000E+09 | -10.00 | 83 |
| 1 | 49 | 24 | 0.0000 | 0.4000E+09 | -10.00 | 84 |
| 1 | 49 | 25 | 0.0000 | 0.4000E+09 | -10.00 | 85 |
| 1 | 48 | 19 | 0.0000 | 0.4000E+09 | -10.00 | 86 |
| 1 | 48 | 20 | 0.0000 | 0.4000E+09 | -10.00 | 87 |
| 1 | 47 | 15 | 0.0000 | 0.4000E+09 | -10.00 | 88 |
| 1 | 47 | 16 | 0.0000 | 0.4000E+09 | -10.00 | 89 |
| 1 | 47 | 17 | 0.0000 | 0.4000E+09 | -10.00 | 90 |
| 1 | 47 | 18 | 0.0000 | 0.4000E+09 | -10.00 | 91 |
| 1 | 47 | 19 | 0.0000 | 0.4000E+09 | -10.00 | 92 |
| 1 | 46 | 11 | 0.0000 | 0.4000E+09 | -10.00 | 93 |
| 1 | 46 | 12 | 0.0000 | 0.4000E+09 | -10.00 | 94 |
| 1 | 46 | 13 | 0.0000 | 0.4000E+09 | -10.00 | 95 |
| 1 | 46 | 14 | 0.0000 | 0.4000E+09 | -10.00 | 96 |
| 1 | 46 | 15 | 0.0000 | 0.4000E+09 | -10.00 | 97 |
| 1 | 44 | 11 | 0.0000 | 0.4000E+09 | -10.00 | 98 |
| 1 | 45 | 11 | 0.0000 | 0.4000E+09 | -10.00 | 99 |
| 1 | 44 | 10 | 0.0000 | 0.4000E+09 | -10.00 | 100 |
| 1 | 43 | 10 | 0.0000 | 0.4000E+09 | -10.00 | 101 |
| 1 | 43 | 9 | 0.0000 | 0.4000E+09 | -10.00 | 102 |
| 1 | 42 | 9 | 0.0000 | 0.4000E+09 | -10.00 | 103 |
| 1 | 42 | 7 | 0.0000 | 0.4000E+09 | -10.00 | 104 |
| 1 | 42 | 8 | 0.0000 | 0.4000E+09 | -10.00 | 105 |
| 1 | 41 | 7 | 0.0000 | 0.4000E+09 | -10.00 | 106 |
| 1 | 41 | 6 | 0.0000 | 0.4000E+09 | -10.00 | 107 |
| 1 | 40 | 5 | 0.0000 | 0.4000E+09 | -10.00 | 108 |
| 1 | 40 | 6 | 0.0000 | 0.4000E+09 | -10.00 | 109 |
| 1 | 39 | 4 | 0.0000 | 0.4000E+09 | -10.00 | 110 |
| 1 | 39 | 5 | 0.0000 | 0.4000E+09 | -10.00 | 111 |
| 1 | 38 | 3 | 0.0000 | 0.4000E+09 | -10.00 | 112 |
| 1 | 38 | 4 | 0.0000 | 0.4000E+09 | -10.00 | 113 |
| 1 | 37 | 2 | 0.0000 | 0.4000E+09 | -10.00 | 114 |
| 1 | 37 | 3 | 0.0000 | 0.4000E+09 | -10.00 | 115 |
| 1 | 35 | 2 | 0.0000 | 0.4000E+09 | -10.00 | 116 |
| 1 | 36 | 2 | 0.0000 | 0.4000E+09 | -10.00 | 117 |
| 1 | 35 | 3 | 0.0000 | 0.4000E+09 | -10.00 | 118 |
| 1 | 30 | 3 | 0.0000 | 0.4000E+09 | -10.00 | 119 |
| 1 | 31 | 3 | 0.0000 | 0.4000E+09 | -10.00 | 120 |
| 1 | 32 | 3 | 0.0000 | 0.4000E+09 | -10.00 | 121 |
| 1 | 33 | 3 | 0.0000 | 0.4000E+09 | -10.00 | 122 |
| 1 | 34 | 3 | 0.0000 | 0.4000E+09 | -10.00 | 123 |
| 1 | 30 | 4 | 0.0000 | 0.4000E+09 | -10.00 | 124 |
| 1 | 28 | 4 | 0.0000 | 0.4000E+09 | -10.00 | 125 |
| 1 | 29 | 4 | 0.0000 | 0.4000E+09 | -10.00 | 126 |
| 1 | 26 | 5 | 0.0000 | 0.4000E+09 | -10.00 | 127 |
| 1 | 27 | 5 | 0.0000 | 0.4000E+09 | -10.00 | 128 |
| 1 | 28 | 5 | 0.0000 | 0.4000E+09 | -10.00 | 129 |
| 1 | 26 | 6 | 0.0000 | 0.4000E+09 | -10.00 | 130 |
| 1 | 26 | 7 | 0.0000 | 0.4000E+09 | -10.00 | 131 |
| 1 | 25 | 7 | 0.0000 | 0.4000E+09 | -10.00 | 132 |
| 1 | 25 | 8 | 0.0000 | 0.4000E+09 | -10.00 | 133 |
| 1 | 24 | 8 | 0.0000 | 0.4000E+09 | -10.00 | 134 |
| 1 | 24 | 9 | 0.0000 | 0.4000E+09 | -10.00 | 135 |
| 1 | 23 | 9 | 0.0000 | 0.4000E+09 | -10.00 | 136 |
| 1 | 23 | 10 | 0.0000 | 0.4000E+09 | -10.00 | 137 |
| 1 | 22 | 10 | 0.0000 | 0.4000E+09 | -10.00 | 138 |
| 1 | 22 | 11 | 0.0000 | 0.4000E+09 | -10.00 | 139 |
| 1 | 19 | 11 | 0.0000 | 0.4000E+09 | -10.00 | 140 |
| 1 | 20 | 11 | 0.0000 | 0.4000E+09 | -10.00 | 141 |
| 1 | 21 | 11 | 0.0000 | 0.4000E+09 | -10.00 | 142 |
| 1 | 14 | 12 | 0.0000 | 0.4000E+09 | -10.00 | 143 |
| 1 | 15 | 12 | 0.0000 | 0.4000E+09 | -10.00 | 144 |
| 1 | 16 | 12 | 0.0000 | 0.4000E+09 | -10.00 | 145 |
| 1 | 17 | 12 | 0.0000 | 0.4000E+09 | -10.00 | 146 |
| 1 | 18 | 12 | 0.0000 | 0.4000E+09 | -10.00 | 147 |
| 1 | 19 | 12 | 0.0000 | 0.4000E+09 | -10.00 | 148 |
| 1 | 12 | 11 | 0.0000 | 0.4000E+09 | -10.00 | 149 |
| 1 | 13 | 11 | 0.0000 | 0.4000E+09 | -10.00 | 150 |
| 1 | 14 | 11 | 0.0000 | 0.4000E+09 | -10.00 | 151 |
| 1 | 5 | 10 | 0.0000 | 0.4000E+09 | -10.00 | 152 |
| 1 | 6 | 10 | 0.0000 | 0.4000E+09 | -10.00 | 153 |
| 1 | 7 | 10 | 0.0000 | 0.4000E+09 | -10.00 | 154 |
| 1 | 8 | 10 | 0.0000 | 0.4000E+09 | -10.00 | 155 |
| 1 | 9 | 10 | 0.0000 | 0.4000E+09 | -10.00 | 156 |
| 1 | 10 | 10 | 0.0000 | 0.4000E+09 | -10.00 | 157 |
| 1 | 11 | 10 | 0.0000 | 0.4000E+09 | -10.00 | 158 |
| 1 | 12 | 10 | 0.0000 | 0.4000E+09 | -10.00 | 159 |
| 1 | 4 | 11 | 0.0000 | 0.4000E+09 | -10.00 | 160 |

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| LAYER | ROW | COL | STAGE | CONDUCTANCE | BOTTOM ELEVATION | RIVER REACH |
|---|---|---|---|---|---|---|
| 1 | 2 | 13 | 0.0000 | 0.4000E+09 | -10.00 | 1 |
| 1 | 2 | 14 | 0.0000 | 0.4000E+09 | -10.00 | 2 |
| 1 | 2 | 15 | 0.0000 | 0.4000E+09 | -10.00 | 3 |
| 1 | 2 | 16 | 0.0000 | 0.4000E+09 | -10.00 | 4 |
| 1 | 2 | 17 | 0.0000 | 0.4000E+09 | -10.00 | 5 |
| 1 | 3 | 17 | 0.0000 | 0.4000E+09 | -10.00 | 6 |
| 1 | 3 | 18 | 0.0000 | 0.4000E+05 | -10.00 | 7 |
| 1 | 3 | 19 | 0.0000 | 0.4000E+05 | -10.00 | 8 |
| 1 | 3 | 20 | 0.0000 | 0.4000E+05 | -10.00 | 9 |
| 1 | 4 | 20 | 0.0000 | 0.4000E+05 | -10.00 | 10 |
| 1 | 4 | 21 | 0.0000 | 0.4000E+05 | -10.00 | 11 |
| 1 | 4 | 22 | 0.0000 | 0.4000E+05 | -10.00 | 12 |
| 1 | 5 | 22 | 0.0000 | 0.4000E+05 | -10.00 | 13 |
| 1 | 5 | 23 | 0.0000 | 0.4000E+05 | -10.00 | 14 |
| 1 | 6 | 23 | 0.0000 | 0.4000E+05 | -10.00 | 15 |
| 1 | 6 | 24 | 0.0000 | 0.4000E+05 | -10.00 | 16 |
| 1 | 7 | 24 | 0.0000 | 0.4000E+05 | -10.00 | 17 |
| 1 | 7 | 25 | 0.0000 | 0.4000E+05 | -10.00 | 18 |
| 1 | 8 | 25 | 0.0000 | 0.4000E+05 | -10.00 | 19 |
| 1 | 8 | 26 | 0.0000 | 0.4000E+05 | -10.00 | 20 |
| 1 | 9 | 26 | 0.0000 | 0.4000E+05 | -10.00 | 21 |
| 1 | 9 | 27 | 0.0000 | 0.4000E+05 | -10.00 | 22 |
| 1 | 10 | 27 | 0.0000 | 0.4000E+05 | -10.00 | 23 |
| 1 | 11 | 27 | 0.0000 | 0.4000E+05 | -10.00 | 24 |
| 1 | 11 | 28 | 0.0000 | 0.4000E+05 | -10.00 | 25 |
| 1 | 12 | 28 | 0.0000 | 0.4000E+05 | -10.00 | 26 |
| 1 | 12 | 29 | 0.0000 | 0.4000E+05 | -10.00 | 27 |
| 1 | 13 | 29 | 0.0000 | 0.4000E+05 | -10.00 | 28 |
| 1 | 13 | 30 | 0.0000 | 0.4000E+05 | -10.00 | 29 |
| 1 | 14 | 30 | 0.0000 | 0.4000E+05 | -10.00 | 30 |
| 1 | 14 | 31 | 0.0000 | 0.4000E+05 | -10.00 | 31 |
| 1 | 15 | 31 | 0.0000 | 0.4000E+05 | -10.00 | 32 |
| 1 | 15 | 32 | 0.0000 | 0.4000E+05 | -10.00 | 33 |
| 1 | 16 | 32 | 0.0000 | 0.4000E+05 | -10.00 | 34 |
| 1 | 17 | 32 | 0.0000 | 0.4000E+05 | -10.00 | 35 |
| 1 | 17 | 33 | 0.0000 | 0.4000E+05 | -10.00 | 36 |
| 1 | 18 | 33 | 0.0000 | 0.4000E+05 | -10.00 | 37 |
| 1 | 18 | 34 | 0.0000 | 0.4000E+05 | -10.00 | 38 |
| 1 | 19 | 34 | 0.0000 | 0.4000E+05 | -10.00 | 39 |
| 1 | 20 | 34 | 0.0000 | 0.4000E+05 | -10.00 | 40 |
| 1 | 20 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 41 |
| 1 | 21 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 42 |
| 1 | 22 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 43 |
| 1 | 23 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 44 |
| 1 | 24 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 45 |
| 1 | 25 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 46 |
| 1 | 26 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 47 |
| 1 | 27 | 35 | 0.0000 | 0.4000E+09 | -10.00 | 48 |
| 1 | 28 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 49 |
| 1 | 29 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 50 |
| 1 | 30 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 51 |
| 1 | 31 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 52 |
| 1 | 32 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 53 |
| 1 | 33 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 54 |
| 1 | 34 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 55 |
| 1 | 35 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 56 |
| 1 | 36 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 57 |
| 1 | 37 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 58 |
| 1 | 38 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 59 |
| 1 | 39 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 60 |
| 1 | 40 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 61 |
| 1 | 41 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 62 |
| 1 | 42 | 35 | 0.0000 | 0.4000E+05 | -10.00 | 63 |
| 1 | 42 | 34 | 0.0000 | 0.4000E+05 | -10.00 | 64 |
| 1 | 43 | 34 | 0.0000 | 0.4000E+05 | -10.00 | 65 |
| 1 | 44 | 34 | 0.0000 | 0.4000E+05 | -10.00 | 66 |
| 1 | 45 | 34 | 0.0000 | 0.4000E+05 | -10.00 | 67 |
| 1 | 45 | 33 | 0.0000 | 0.4000E+05 | -10.00 | 68 |
| 1 | 46 | 33 | 0.0000 | 0.4000E+05 | -10.00 | 69 |
| 1 | 46 | 32 | 0.0000 | 0.4000E+05 | -10.00 | 70 |
| 1 | 47 | 32 | 0.0000 | 0.4000E+05 | -10.00 | 71 |
| 1 | 47 | 30 | 0.0000 | 0.4000E+05 | -10.00 | 72 |
| 1 | 47 | 31 | 0.0000 | 0.4000E+05 | -10.00 | 73 |
| 1 | 48 | 25 | 0.0000 | 0.4000E+05 | -10.00 | 74 |
| 1 | 48 | 26 | 0.0000 | 0.4000E+05 | -10.00 | 75 |
| 1 | 48 | 27 | 0.0000 | 0.4000E+05 | -10.00 | 76 |
| 1 | 48 | 28 | 0.0000 | 0.4000E+05 | -10.00 | 77 |
| 1 | 48 | 29 | 0.0000 | 0.4000E+05 | -10.00 | 78 |
| 1 | 48 | 30 | 0.0000 | 0.4000E+05 | -10.00 | 79 |

0.0000 1.3401E-03 3.3514E-03 7.5134E-03 7.6389E-03 8.0773E-03 3.6811E-03 2.7853E-03 2.4862E-03 2.4839E-03
2.2191E-03 2.4976E-03 2.0889E-03 2.0296E-03 9.7712E-04 8.6754E-05
0 32 0.0000 0.0000 0.0000 0.0000 1.8903E-03 1.6734E-03 9.3146E-04 6.7577E-04 8.1047E-04 1.1027E-03
8.5813E-04 1.1255E-03 1.0707E-03 1.0844E-03 1.3949E-03 1.4383E-03 1.3515E-03 1.6346E-03 1.7054E-03 4.2692E-04
5.7075E-04 1.7670E-03 5.2532E-03 8.3900E-03 8.7074E-03 7.6275E-03 6.9038E-03 5.7372E-03 3.4450E-03 2.9108E-03
2.4885E-03 2.7259E-03 2.1186E-03 1.7990E-03 1.1141E-03 9.3603E-05
0 33 0.0000 0.0000 0.0000 2.1004E-04 2.2967E-03 1.8675E-03 9.6114E-04 6.0500E-04 7.4882E-04 1.0091E-03
6.8033E-04 1.0388E-03 6.2783E-04 1.0228E-03 9.3375E-04 6.1641E-04 8.0818E-04 1.7077E-03 1.9611E-03 1.6072E-03
2.6939E-04 7.7850E-04 5.3148E-03 8.3535E-03 8.7439E-03 9.3398E-03 9.1297E-03 7.8284E-03 4.9724E-03 4.0135E-03
3.2533E-03 2.3835E-03 2.1437E-03 2.2168E-03 1.6894E-03 1.3470E-04
0 34 0.0000 0.0000 0.0000 1.8264E-05 1.9542E-03 2.0250E-03 1.6757E-03 7.1915E-04 2.2145E-04 9.7028E-04
7.3741E-04 1.1164E-03 8.3330E-04 7.7622E-04 6.3696E-04 8.6297E-04 9.0407E-04 1.6689E-03 1.9565E-03 8.5384E-04
6.9175E-04 2.3971E-04 4.8080E-03 7.7188E-03 8.3718E-03 8.9631E-03 8.7599E-03 6.2440E-03 4.9176E-03 3.7484E-03
3.1277E-03 2.3287E-03 2.2647E-03 1.9520E-03 1.4817E-03 8.6754E-05
0 35 0.0000 0.0000 0.0000 2.8081E-04 2.0273E-03 2.1780E-03 2.1072E-03 1.5684E-03 3.4245E-04 5.3194E-04
7.6252E-04 1.1232E-03 8.5384E-04 9.5886E-04 9.4516E-04 1.0958E-03 1.6734E-03 1.7602E-03 1.9040E-03 2.1186E-03
8.2416E-04 2.6072E-03 2.0981E-03 7.8147E-03 8.3444E-03 8.4791E-03 7.9471E-03 7.6914E-03 5.7623E-03 4.3514E-03
3.2373E-03 1.4657E-03 1.9383E-03 1.5502E-03 1.6186E-03 4.7943E-05
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5.7075E-04 1.0159E-03 1.1187E-03 8.0133E-04 7.4426E-04 1.2990E-03 1.6597E-03 1.7693E-03 1.8061E-03 2.0935E-03
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1.7282E-03 1.4885E-03 7.1001E-04 5.2509E-04 6.6207E-04 5.6818E-04 8.6526E-04 1.0456E-03 9.9995E-04 1.7716E-03
1.5961E-03 9.1548E-04 5.4335E-03 7.5659E-03 7.8581E-03 7.7668E-03 8.3307E-03 6.9791E-03 4.4153E-03 3.2921E-03
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1.8743E-03 1.8538E-03 1.8332E-03 9.4745E-04 6.0956E-04 5.1139E-04 6.5066E-04 8.8809E-04 1.0936E-03 1.2214E-03
8.5813E-04 4.7030E-04 5.6070E-03 6.9061E-03 6.9426E-03 8.9357E-03 7.8695E-03 5.7920E-03 3.1277E-03 2.4337E-03
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7.4198E-04 1.0433E-03 4.2007E-03 5.6116E-03 6.5958E-03 9.1252E-03 7.4289E-03 4.5820E-03 1.9908E-03 1.4908E-03
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0 41 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 6.2098E-04 1.8036E-03
2.0593E-03 2.0387E-03 1.9976E-03 1.9999E-03 2.0456E-03 1.9702E-03 2.0433E-03 1.0707E-03 3.1505E-04 2.2145E-04
1.2739E-03 1.3104E-03 2.8538E-03 4.5500E-03 5.0705E-03 8.2416E-03 6.0477E-03 1.5182E-03 2.2647E-03 1.0707E-03
5.2052E-04 1.0479E-03 1.7488E-03 1.8675E-03 6.3924E-04 0.0000
0 42 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 7.5339E-05
1.6232E-03 1.9109E-03 1.9816E-03 2.0615E-03 2.1028E-03 2.4542E-03 3.4336E-03 2.6414E-03 8.9037E-04 1.6118E-03
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1.2716E-03 1.7853E-03 1.8538E-03 1.7511E-03 2.9907E-04 0.0000
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2.9222E-04 1.4223E-03 1.8264E-03 2.0205E-03 2.1803E-03 2.3264E-03 2.3720E-03 2.2214E-03 1.8768E-03 1.8995E-03
1.6186E-03 2.0273E-03 2.8172E-03 3.8628E-03 2.9337E-03 3.0861E-03 2.6528E-03 2.5045E-03 2.2077E-03 2.4154E-03
2.0410E-03 1.9177E-03 1.8081E-03 1.3652E-03 2.9679E-04 0.0000
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0.0000 0.0000 7.3513E-04 1.7282E-03 2.0798E-03 2.1643E-03 1.9337E-03 1.7579E-03 1.8789E-03 1.8150E-03
2.1163E-03 1.9223E-03 2.0250E-03 2.4793E-03 2.0205E-03 2.2762E-03 2.0961E-03 1.6689E-03 2.4748E-03 1.8561E-03
2.0159E-03 1.8652E-03 1.7899E-03 1.0616E-03 6.6207E-05 0.0000
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0.0000 0.0000 5.9130E-04 8.1503E-04 7.5587E-04 2.0593E-03 1.9931E-03 2.1072E-03 2.1965E-03 2.0935E-03
2.9268E-03 1.9428E-03 2.1163E-03 2.3061E-03 1.9908E-03 2.0684E-03 2.3309E-03 1.7579E-03 2.3903E-03 1.8903E-03
1.5935E-03 1.7419E-03 1.3219E-03 2.6786E-04 0.0000 0.0000
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2.7442E-03 2.1346E-03 1.9086E-03 2.0684E-03 1.6940E-03 1.8584E-03 2.0570E-03 1.9246E-03 1.7944E-03 1.8928E-03
1.8095E-03 8.1503E-04 3.4245E-05 0.0000 0.0000 0.0000
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1.2237E-03 1.9999E-03 1.8768E-03 1.9908E-03 2.0250E-03 1.9132E-03 1.2876E-03 3.1505E-04 3.5843E-04 1.7123E-04
1.5068E-04 0.0000 0.0000 0.0000 0.0000 0.0000
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164 RIVER REACHES